



New Results of Electron Antineutrino Disappearance From the Daya Bay Experiment

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On behalf of the Daya Bay Collaboration

*TAUP 2013, Asilomar
Sep 12, 2013*

Neutrino Mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\nu_i\rangle$$

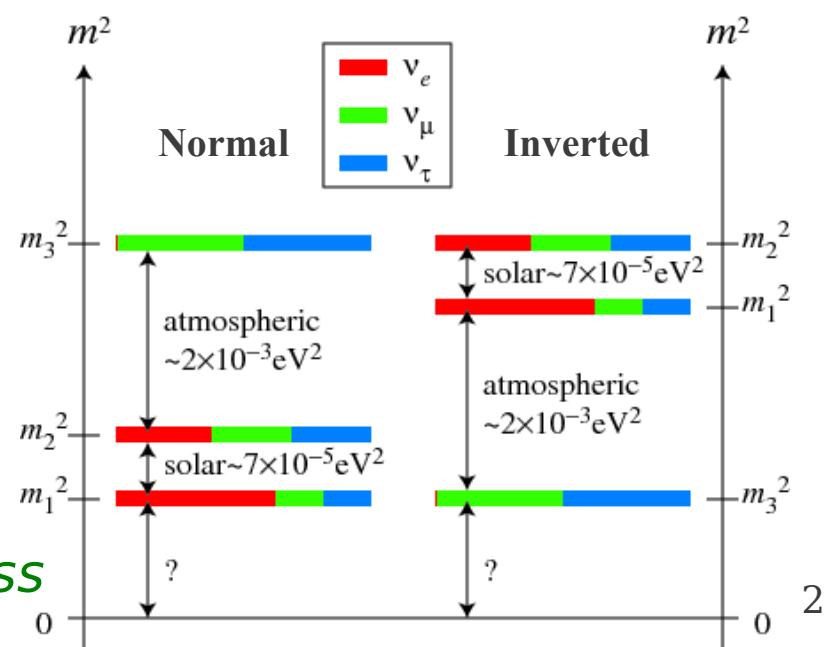
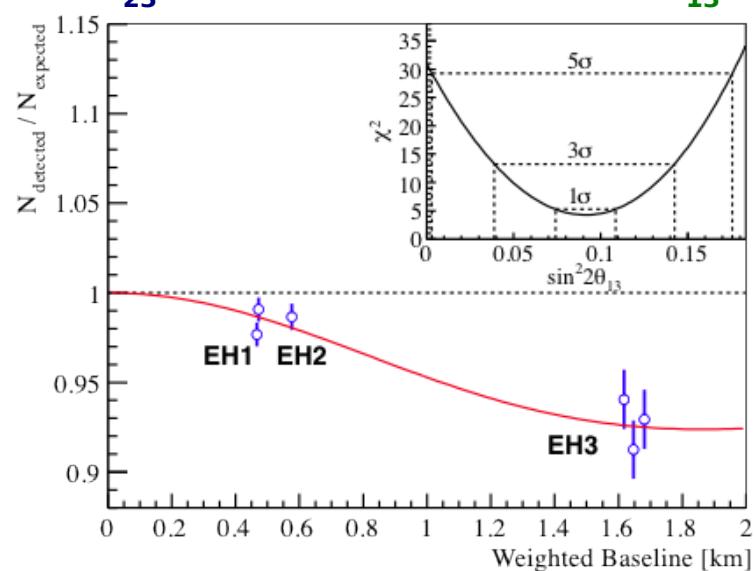
PMNS Mixing Matrix

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

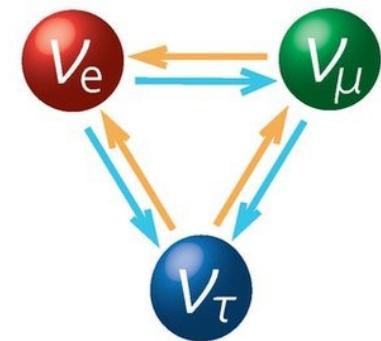
atmospheric **reactor** **solar**

$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 34^\circ$

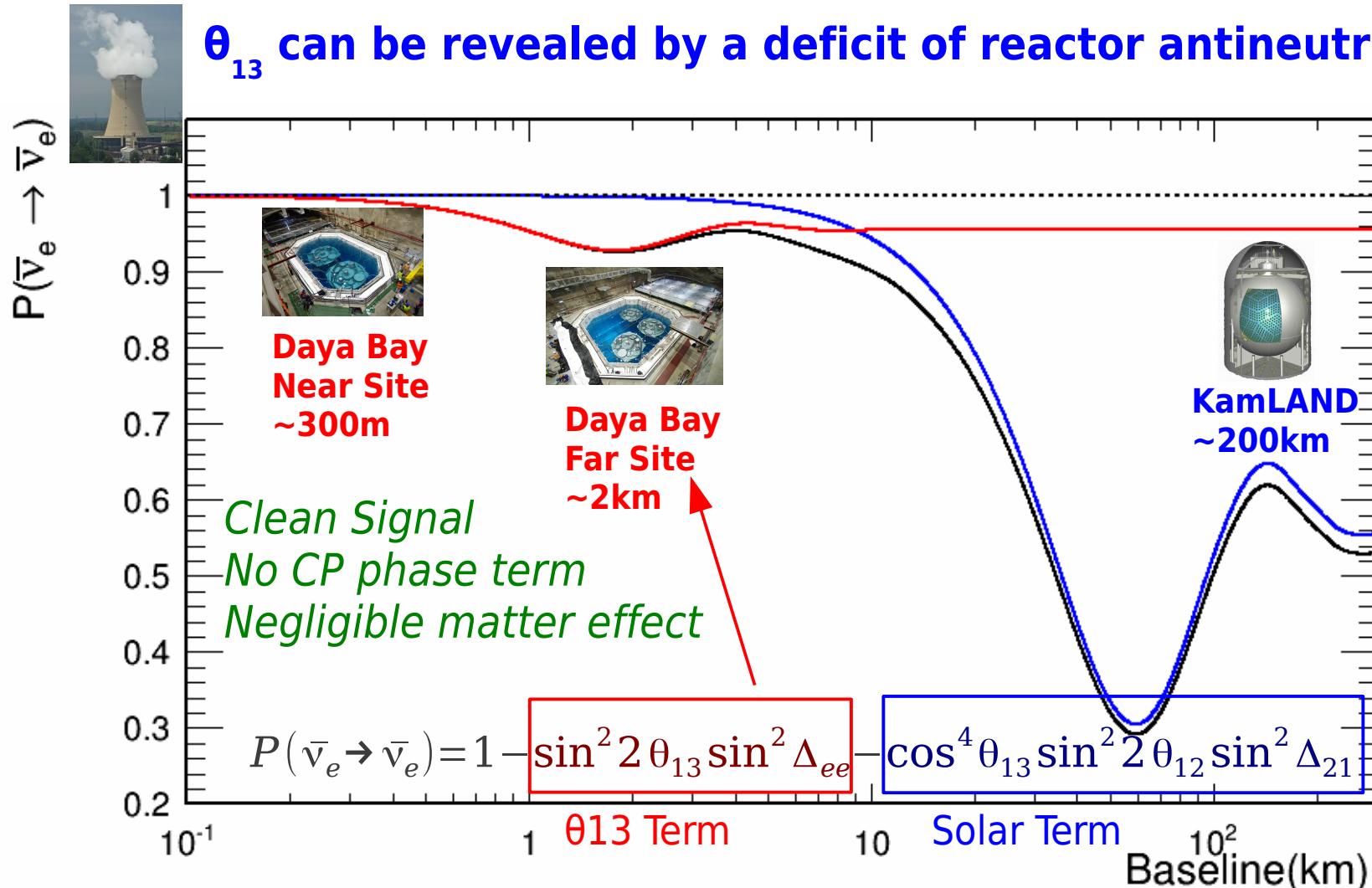
$c_{ij} \equiv \cos \theta_{ij}$ $s_{ij} \equiv \sin \theta_{ij}$



The gateway for determining neutrino mass hierarchy and CP phase is open



Reactor Neutrinos Oscillation



Define

$$\begin{aligned}\sin^2 \Delta_{ee} &= \cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32} \\ &\approx 0.7 \cdot \sin^2 \Delta_{31} + 0.3 \cdot \sin^2 \Delta_{32}\end{aligned}$$

$$\Delta_{ij} \simeq 1.27 \Delta m_{ij}^2 (eV^2) \frac{L(m)}{E(MeV)}$$

Relative Measurement

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}} \right) \left(\frac{L_n}{L_f} \right)^2 \left(\frac{\epsilon_f}{\epsilon_n} \right) \left[\frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

Far/Near
Neutrino Ratio

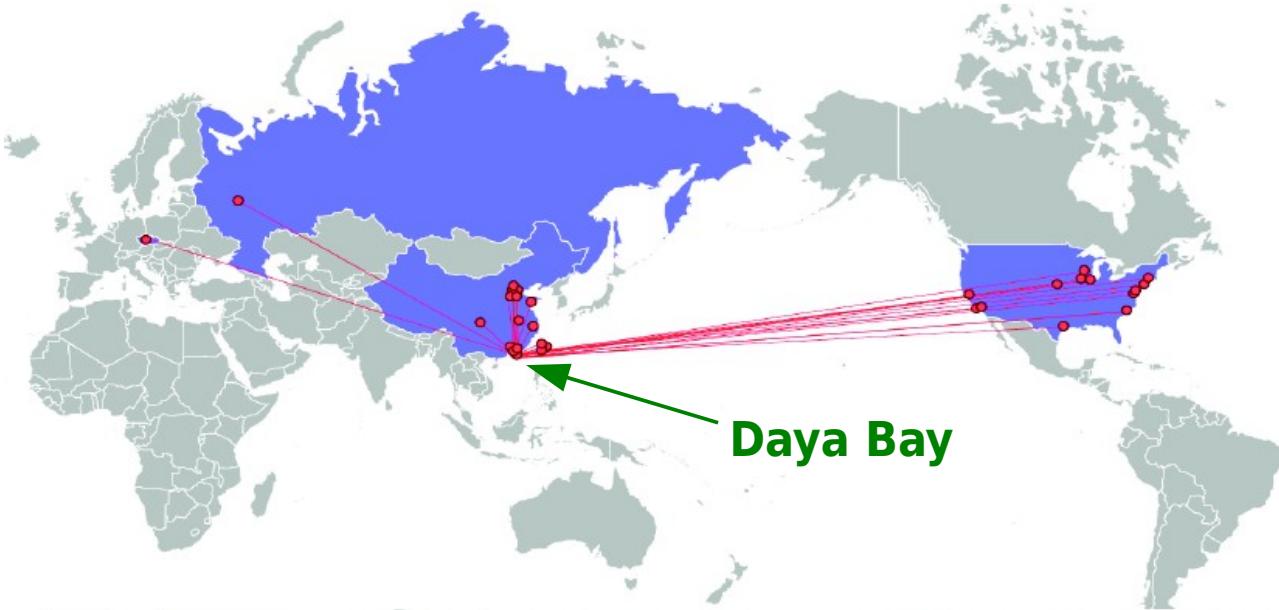
Detector
Target Mass

Distance
from
Reactor

Detector
Efficiency

Survival Probability
(θ₁₃)

Daya Bay Collaboration



Asia (21)

Beijing Normal Univ., Chendu Univ. of Sci. and Tech., CGNPG, CIAE, Chinese Univ. of Hong Kong, Dongguan Univ. of Tech., IHEP, Nanjing Univ., Nankai Univ., National Chiao Tung Univ., National Taiwan Univ., National United Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., Univ. of Hong Kong, USTC, Xi'an Jiao Tong Univ., Zhongshan Univ.

North America (17)

BNL, Caltech, LBNL, Illinois Inst. Tech., Iowa State Univ., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Illinois-Urbana-Champaign, Univ. of Wisconsin, Virginia Tech., William & Mary, Siena College, Yale

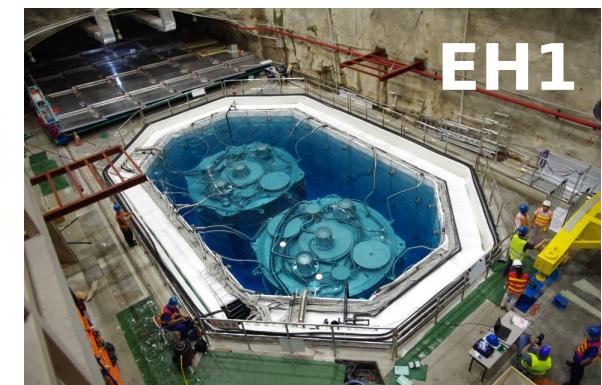
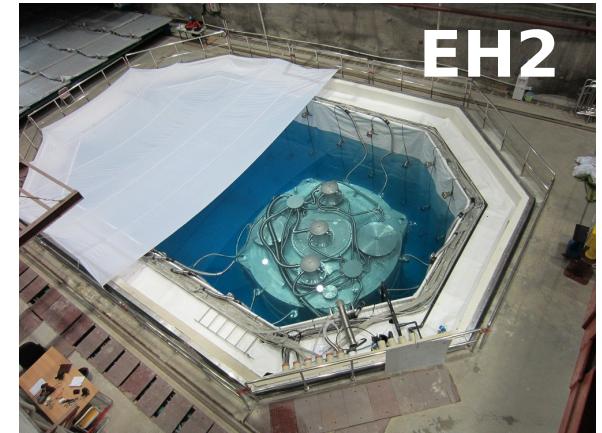
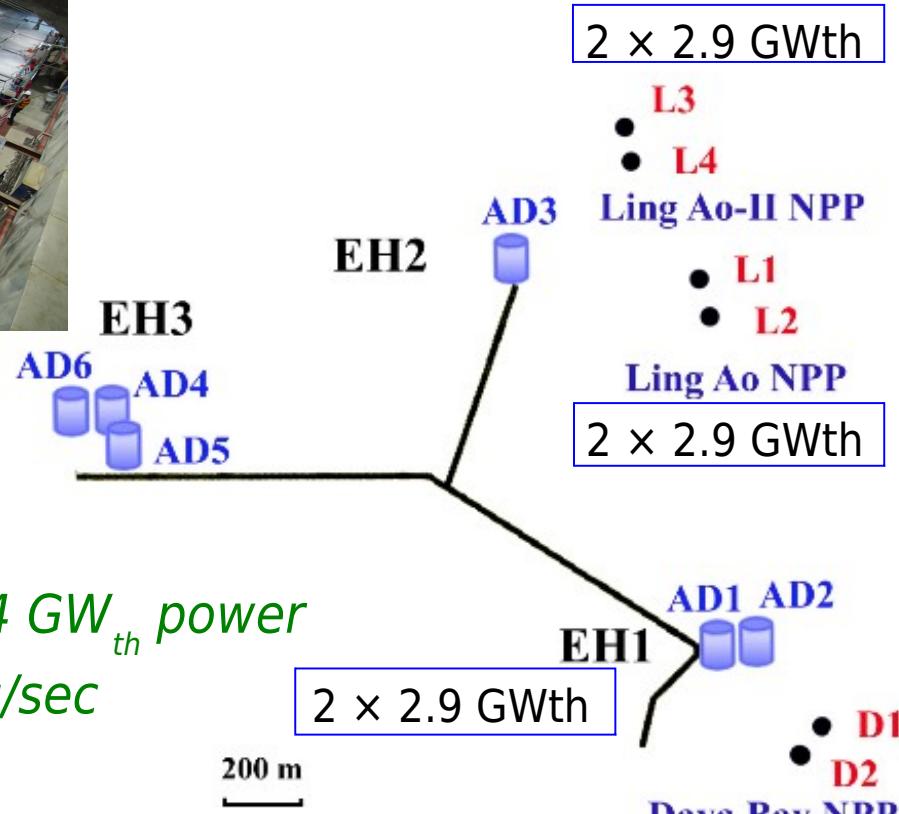
Europe (2)

Charles University, Czech Republic; JINR, Dubna, Russia

**40 institutions
~230 collaborators**

Daya Bay Experimental Layout

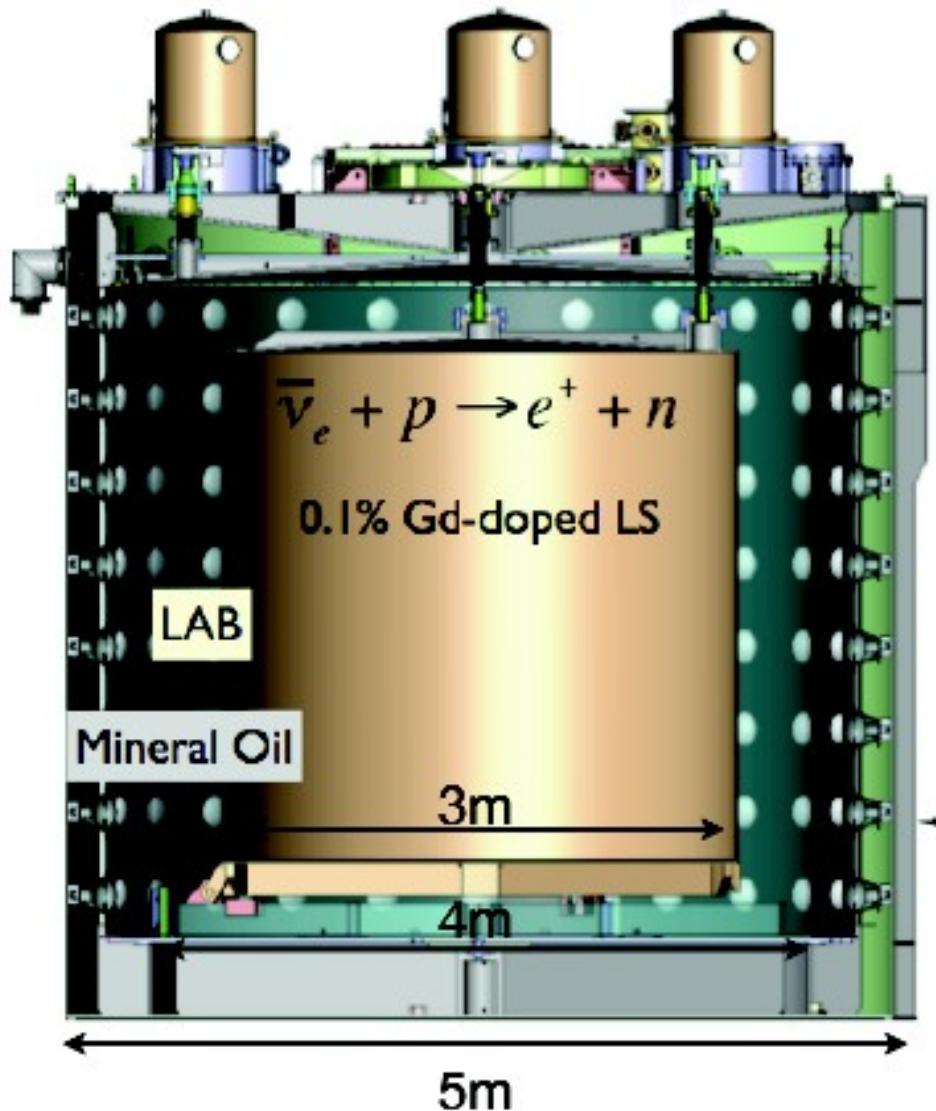
6 Antineutrino Detectors (ADs) in 3 underground experimental halls (EHs).



	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

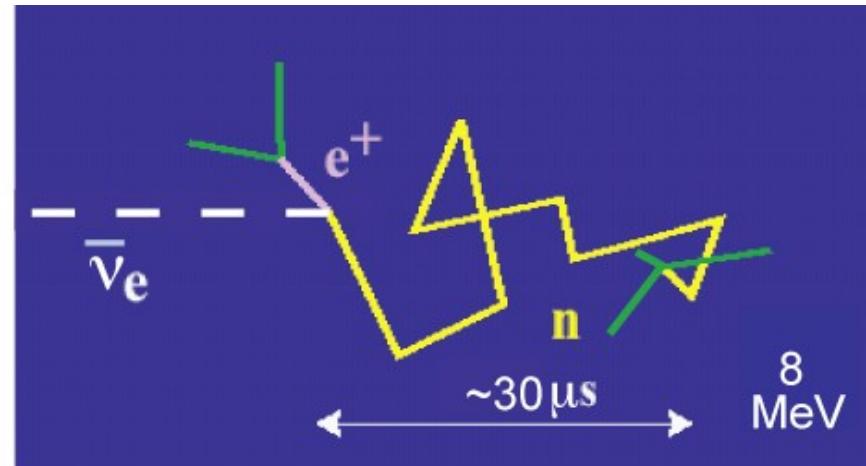
TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Daya Bay Antineutrino Detectors (AD)



6 functionally identical 3-zone detectors

Very well defined target region



Inverse beta decay (IBD)

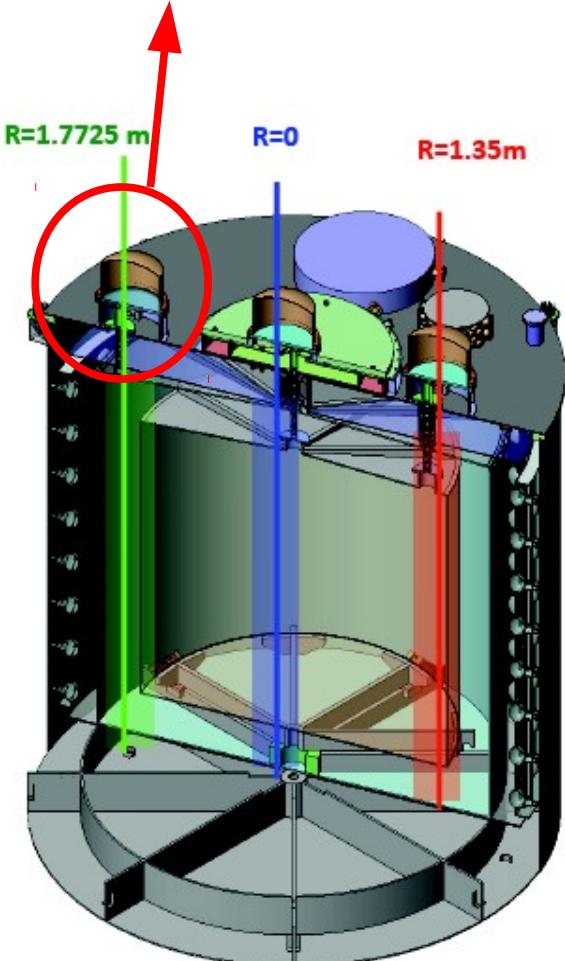
Prompt Positron:

- Carries antineutrino energy
- $E_{Prompt} \approx E_\nu - 0.8 \text{ MeV}$

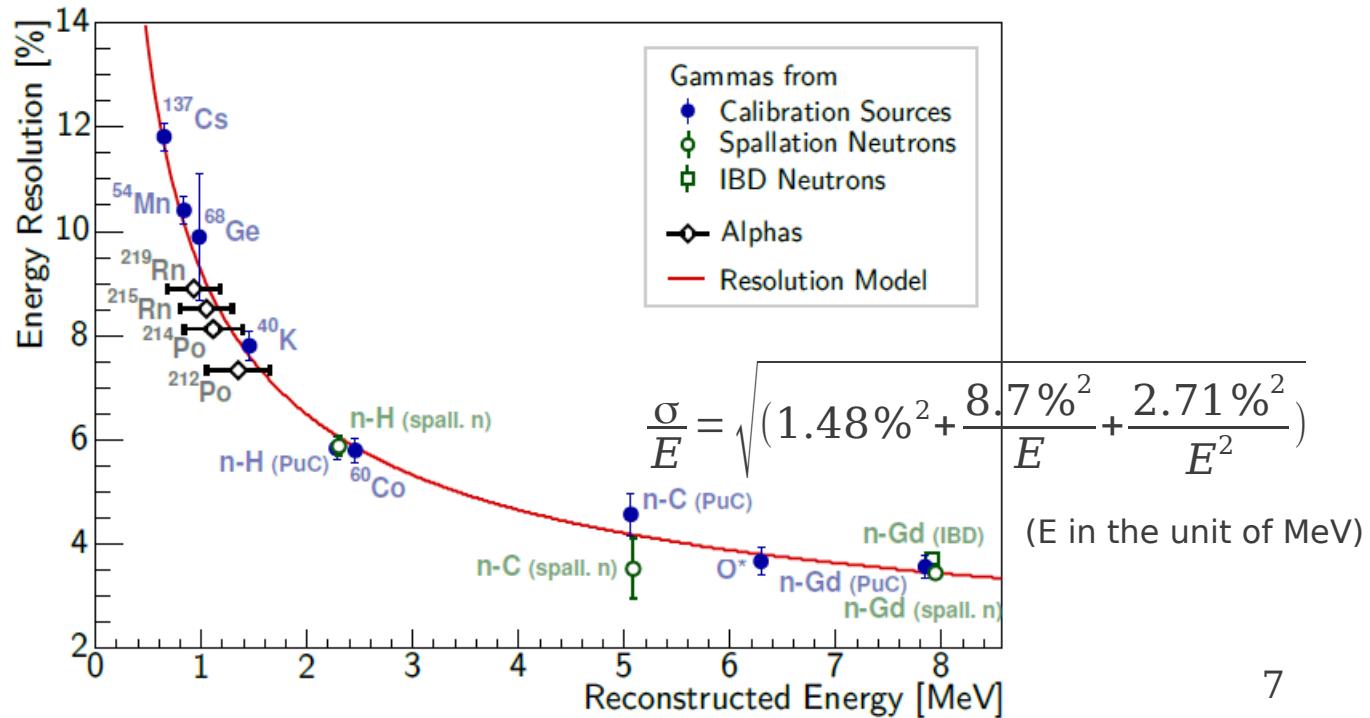
Delayed Neutron Capture

- $\langle \sum E_\gamma \rangle = 8.05 \text{ MeV}$
- Efficiently tag antineutrino signal

Automatic Calibration Units (ACU)



- 3 sources for each 3 z axis on a turntable
 - ^{68}Ge (2 x 0.511 MeV γ 's)
 - ^{241}Am - ^{13}C neutron source (3.5 MeV n) + ^{60}Co gamma source (1.173+1.332 MeV γ 's)
 - LED diffuser ball for timing and gain
- Temporary special calibration sources:
 - γ : ^{137}Cs (0.662MeV), ^{54}Mn (0.835MeV), ^{40}K (1.461MeV)
 - n: ^{241}Am ^9Be , ^{239}Pu ^{13}C



Analysis Data Sets

A. Two-detector data taking:

- Sep 23, 2011 - Dec. 23, 2011 [90 days]
- Side-by-side comparison of 2 detectors
- NIM A 685, 78-97 (2012)

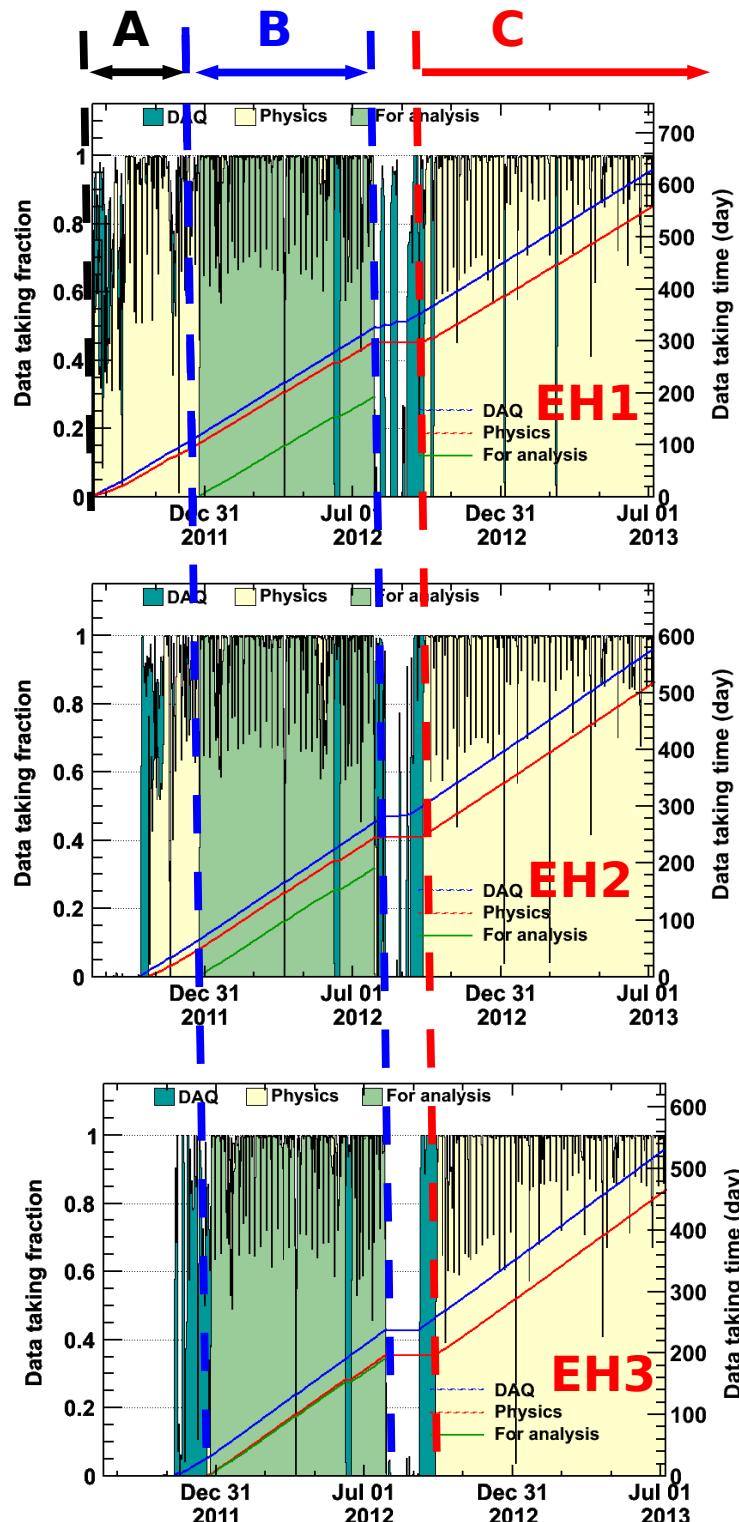
B. Six-detector data taking:

[This analysis]

- Dec. 24, 2011 - Jul. 28, 2012 [217 days]
- Full 6AD data set, 4 times more statistics than PRL result
- Previous θ_{13} measurements:
 - PRL. 108, 171803 (2012) [55 days]
 - CPC 37, 011001 (2013) [139 days]

C. Eight-detector data taking:

- Start from Oct.28, 2012



Antineutrino (IBD) Selection

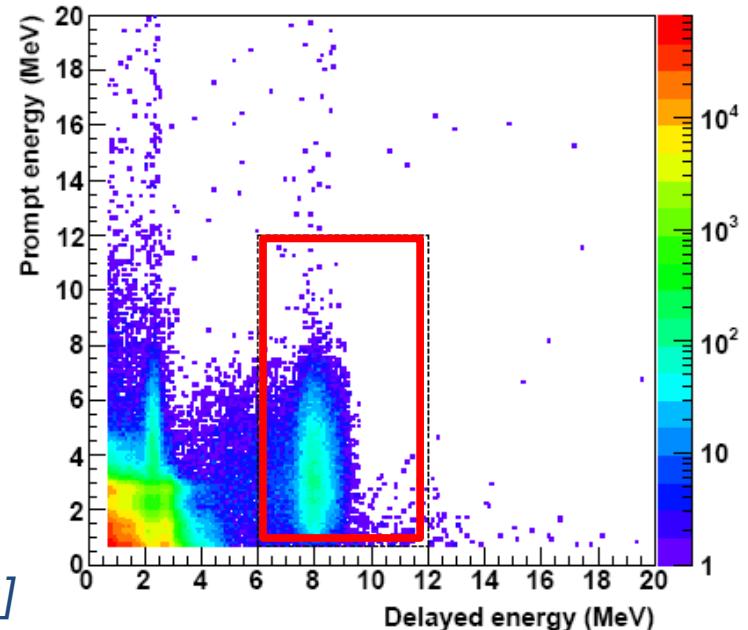
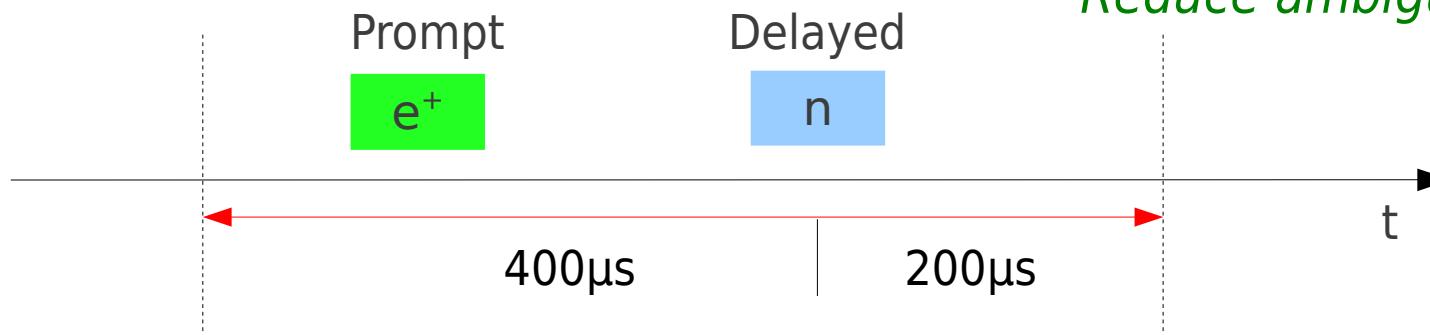
Use IBD Prompt + Delayed correlated signal to select antineutrinos

Selection:

- Reject PMT Flashers
- Prompt Positron: $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
- Delayed Neutron: $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
- Capture time: $1 \mu\text{s} < \Delta t < 200 \mu\text{s}$
- Muon Veto for delay neutron:
Water Pool Muon ($n\text{Hit}>12$): Reject $[-2\mu\text{s}, 600\mu\text{s}]$
AD Muon ($>3000\text{PE}$): Reject $[-2\mu\text{s}, 1400\mu\text{s}]$
AD Shower Muon ($>3 \times 10^5 \text{ PE}$): Reject $[-2\mu\text{s}, 0.4\text{s}]$

Multiplicity:

No additional prompt-like signal in $400\mu\text{s}$ before the delayed signal, and no delayed-like signal in $200\mu\text{s}$ after the delayed signal



Reduce ambiguity pairs

Data Set Summary

	EH1	EH2	EH3	AD4	AD5	AD6
	AD1	AD2	AD3			
Antineutrino candidates	101290	102519	92912	13964	13894	13731
DAQ live time (day)		191.001	189.645		189.779	
Efficiency	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (/day/AD)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast neutron (/day/AD)*		0.92±0.46	0.62±0.31		0.04±0.02	
⁸ He/ ⁹ Li (/day/AD)*		2.40±0.86	1.20±0.63		0.22±0.06	
Am-C corr. (/day/AD)*				0.26±0.12		
¹³ C(α, n) ¹⁶ O (/day/AD)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate* (/day/AD)	653.30 ± 2.31	664.15 ± 2.33	581.97 ± 2.07	73.31 ± 0.66	73.03 ± 0.66	72.20 ± 0.66

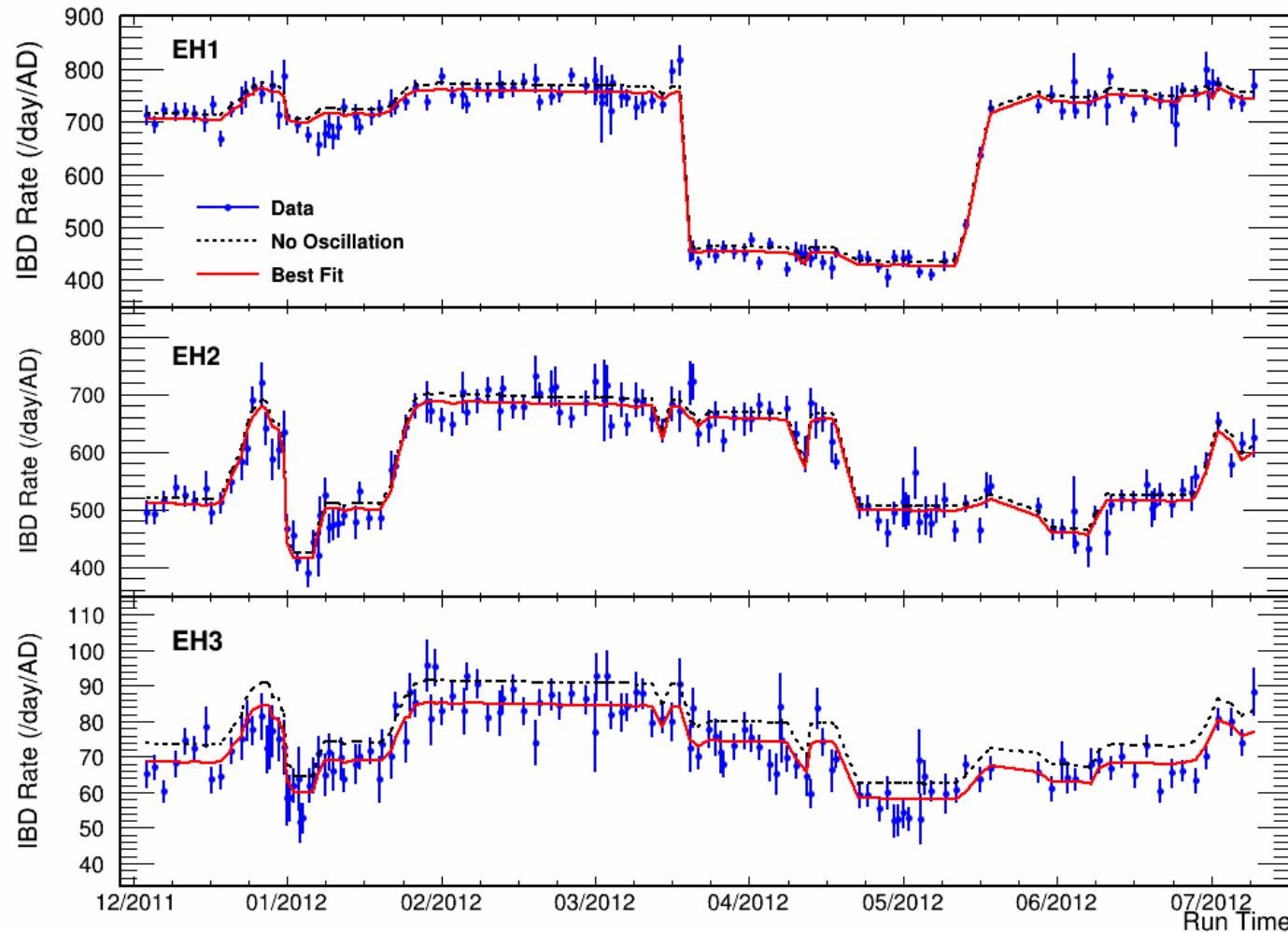
*rate are muon and multiplicity cut efficiency corrected.

Over 300,000 antineutrino interactions

Total Background/Signal ratio is ~5% at Far site, ~2% at Near site 10

Antineutrino Rate .vs. Time

IBD rate is fully correlated with reactor flux expectations



- Predicted rate assumes no oscillation
- *Normalization is determined by fit to data*
- Absolute normalization is within a few percent of expectations

Detector Uncertainty Summary

For near/far oscillation, only uncorrelated uncertainties are used

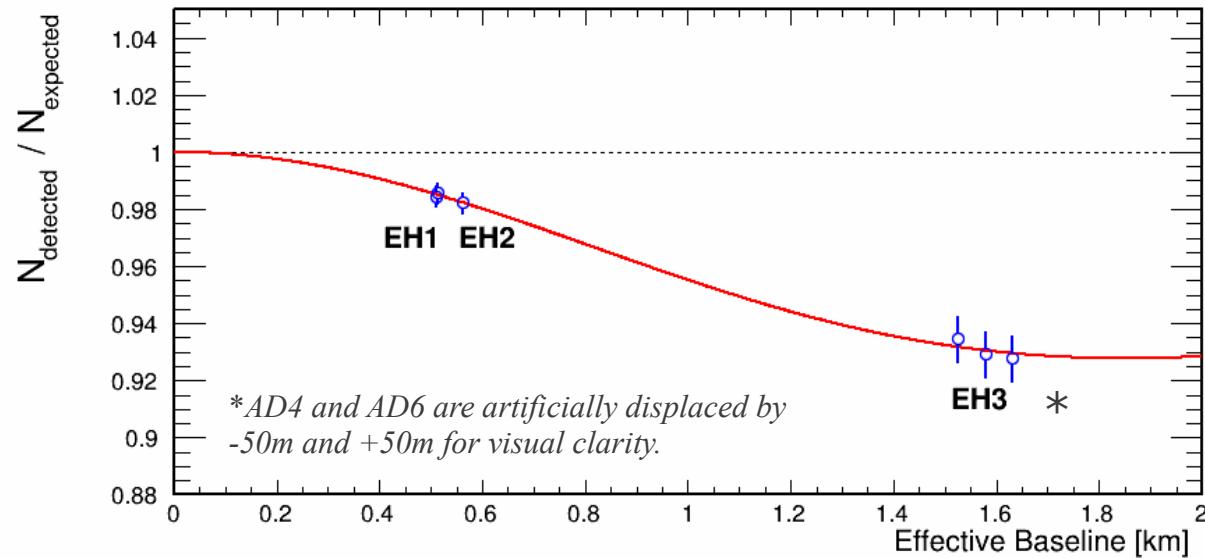
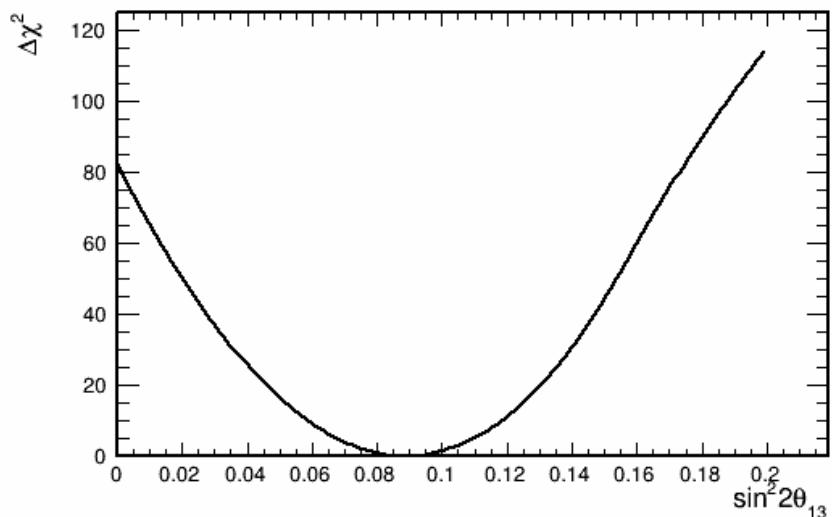
Detector		
	Efficiency	Correlated
Target Protons		0.47%
Flasher cut	99.98%	0.01%
Delayed energy cut	90.9%	0.6%
Prompt energy cut	99.88%	0.10%
Multiplicity cut		0.02%
Capture time cut	98.6%	0.12%
Gd capture ratio	83.8%	0.8%
Spill-in	105.0%	1.5%
Livetime	100.0%	0.002%
Combined	78.8%	1.9%

Largest systematics are smaller than far site statistics (~0.5%)

Reactor	
Correlated	Uncorrelated
Energy/fission	0.2%
$\bar{\nu}_e$ /fission	3%
Combined	3%

Influence of uncorrelated reactor systematics further reduced by far vs. near measurement

Rate Only Analysis



$$\sin^2 2\theta_{13} = 0.089 \pm 0.009$$

$$\chi^2/NDF = 0.48/4$$

- **Rate only analysis**
 - Use maximum likelihood method
 - Far vs. near relative measurement [absolute rate is not constrained]
 - Constrain $|\Delta m^2_{ee}|$ to the MINOS $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (eV^2)$ [PRL. 110, 251801 \(2013\)](#)
 - Consistent results obtained by different reactor flux models

In order to further improve the measurement, we can add the spectrum χ^2 information.

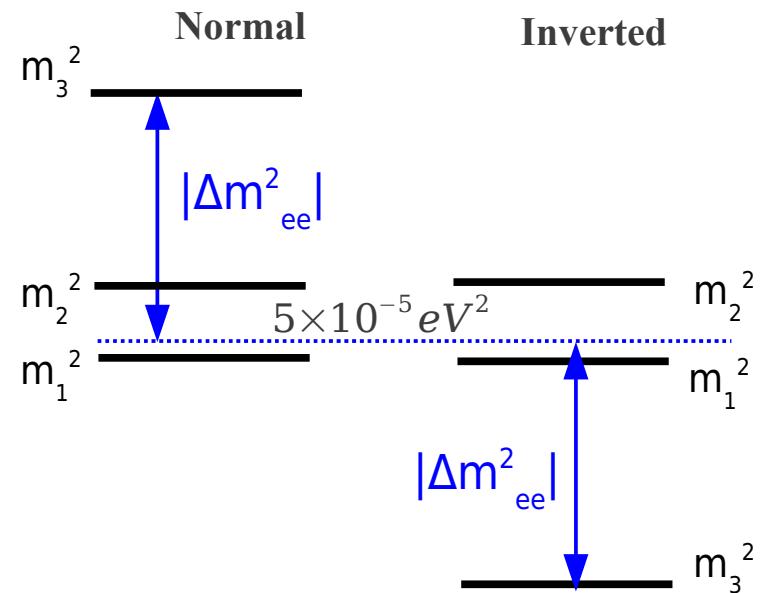
Spectral Oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \boxed{\sin^2 2\theta_{13}} \sin^2(1.27 \boxed{\Delta m_{ee}^2 \frac{L}{E}})$$

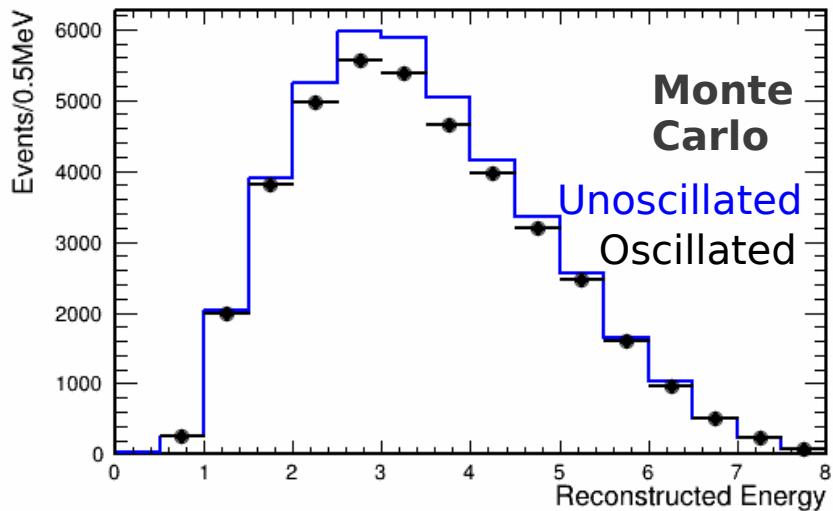
Due to the short baseline, Daya Bay can observe one effective $|\Delta m_{ee}^2|$, which is a constant shift of $|\Delta m_{32}^2|$ for two mass hierarchies

$$|\Delta m_{ee}^2| \approx |\Delta m_{32}^2| \pm 5 \times 10^{-5} \text{ eV}^2$$

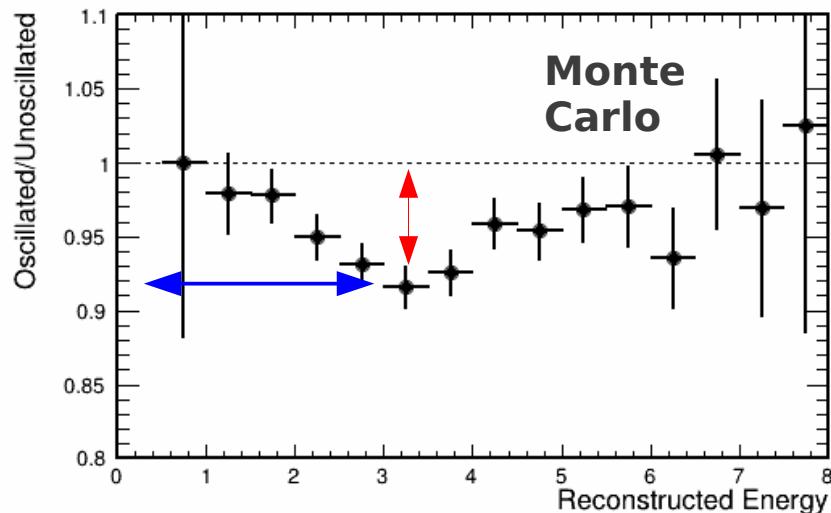
+(-) for Normal (Inverted) Mass Hierarchy



Far Site Spectrum

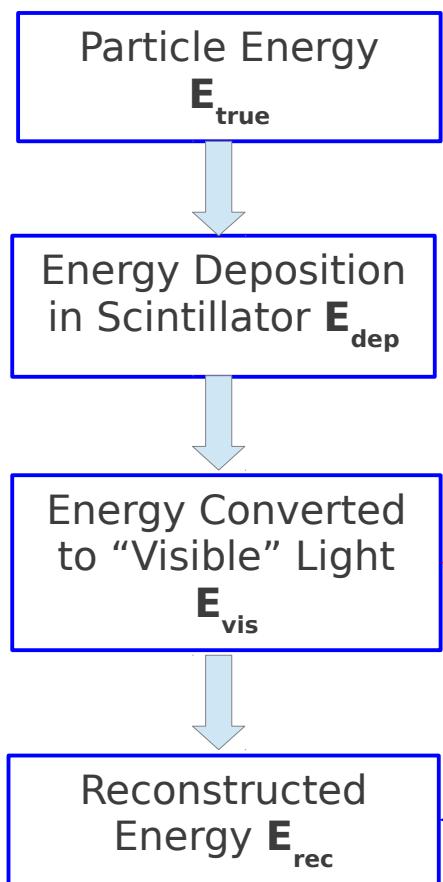


Spectrum Ratio



We can also measure $|\Delta m_{ee}^2|$ thanks to the “large” θ_{13}

Energy Response Model



Energy response parameterization

$$f = \frac{E_{rec}}{E_{true}}(E_{true}) = \frac{E_{vis}}{E_{true}}(E_{true}) \cdot \frac{E_{rec}}{E_{vis}}(E_{vis})$$

Scintillator energy response

Readout electronics response

Scintillator energy response

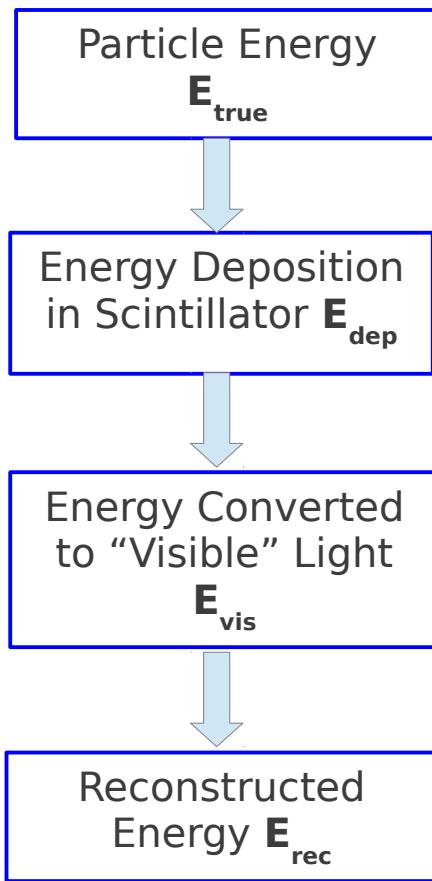
- Scintillator quenching effect
- Cerenkov radiation

Readout electronics response

- Charge collection efficiency
- PMT signal shaping
- Others

Detector energy response model converts particle true kinetic energy to the reconstructed energy

Electron Energy Response Model



Energy Response Parameterization

$$f = \frac{E_{rec}}{E_{true}}(E_{true}) = \frac{E_{vis}}{E_{true}}(E_{true}) \cdot \frac{E_{rec}}{E_{vis}}(E_{vis})$$

Scintillator energy response

- **Electrons**
 - 2 parameterizations to model electron scintillator response

$$\frac{E_{vis}}{E_{true}}(E_{true}) = \frac{1 + p3 \cdot E_{true}}{1 + p1 \cdot e^{-p2 \cdot E_{true}}}$$

$$\frac{E_{vis}}{E_{true}}(E_{true}) = f_q(E_{true}; k_B) + k_C \cdot f_C(E_{true})$$

k_B : Birk's constant

k_C : Cherenkov contribution

Readout electronics response

- Empirical parameterization: exponential

Gamma and Positron Energy Response Model

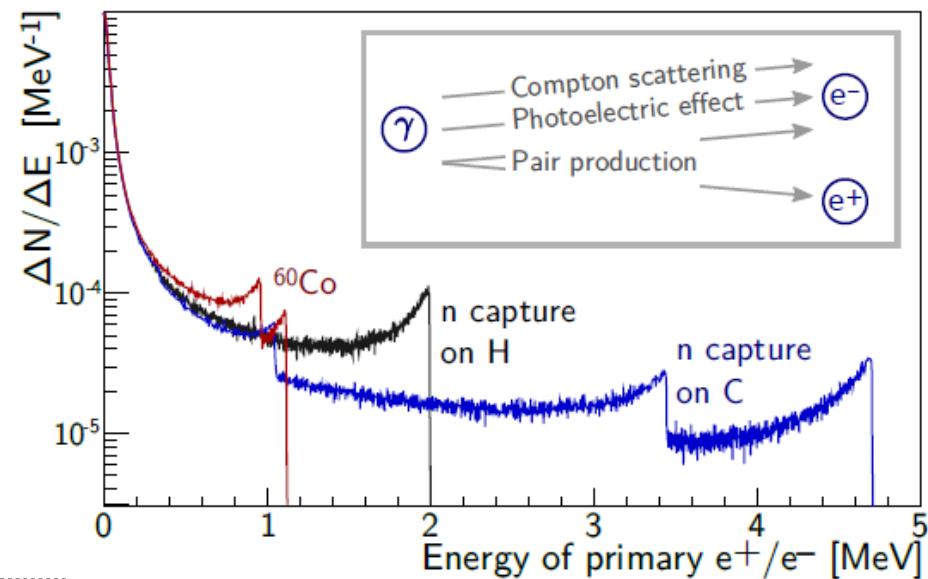
Energy response parameterization

$$f = \frac{E_{rec}}{E_{true}}(E_{true}) = \boxed{\frac{E_{vis}}{E_{true}}(E_{true})} \cdot \boxed{\frac{E_{rec}}{E_{vis}}(E_{vis})}$$

Scintillator energy response

- **Gamma and Positron Response**
 - Gamma connected electron model through MC
 - Positron assumed to interact with the scintillator in the same way as electrons:

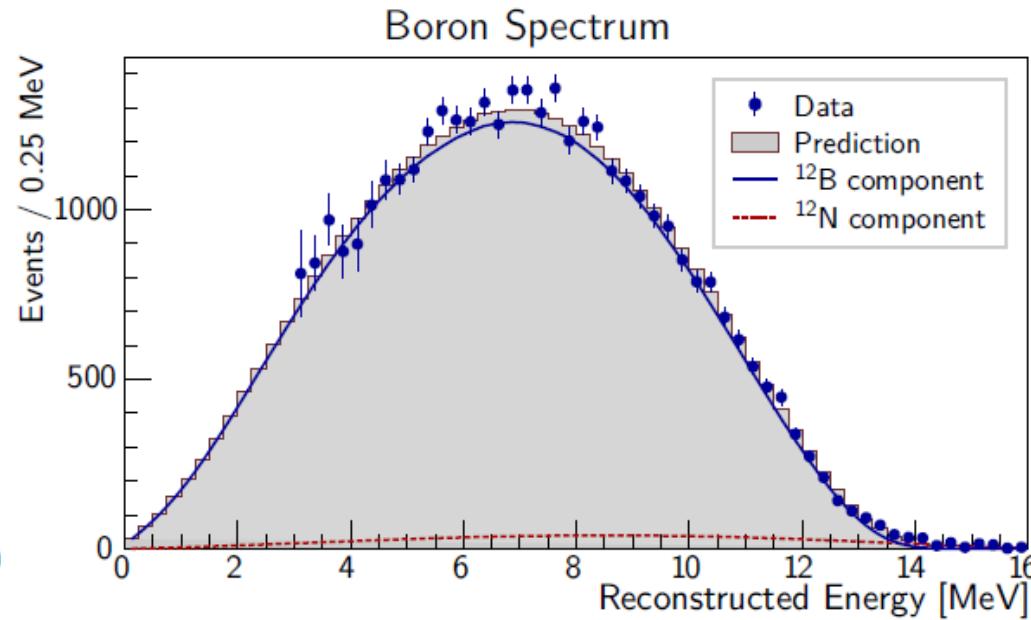
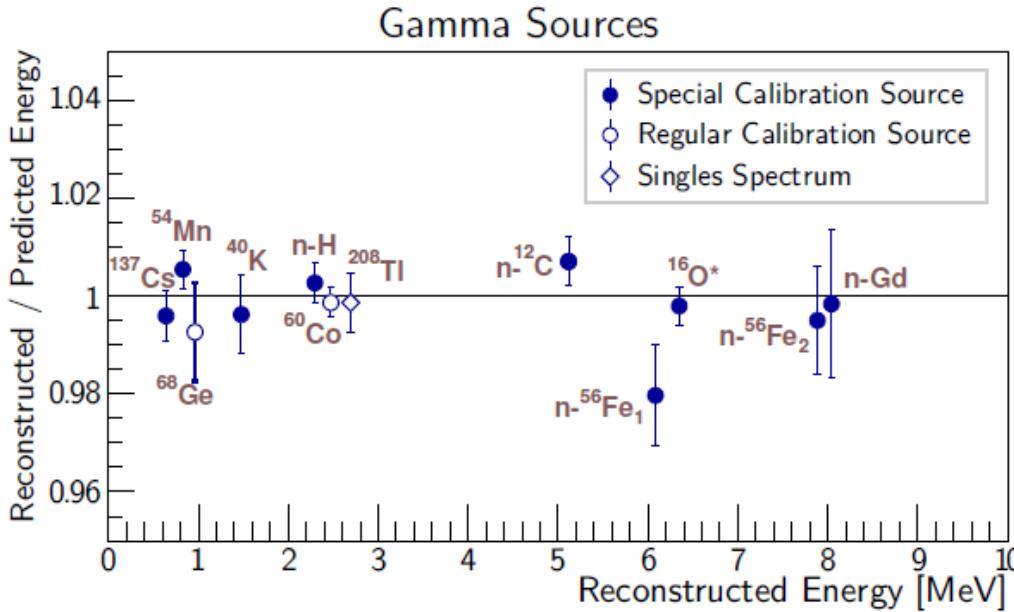
$$E_{vis}^{e+} = E_{vis}^{e-} + 2 \cdot E_{vis}^{\gamma} (0.511 \text{ MeV})$$



Readout electronics response

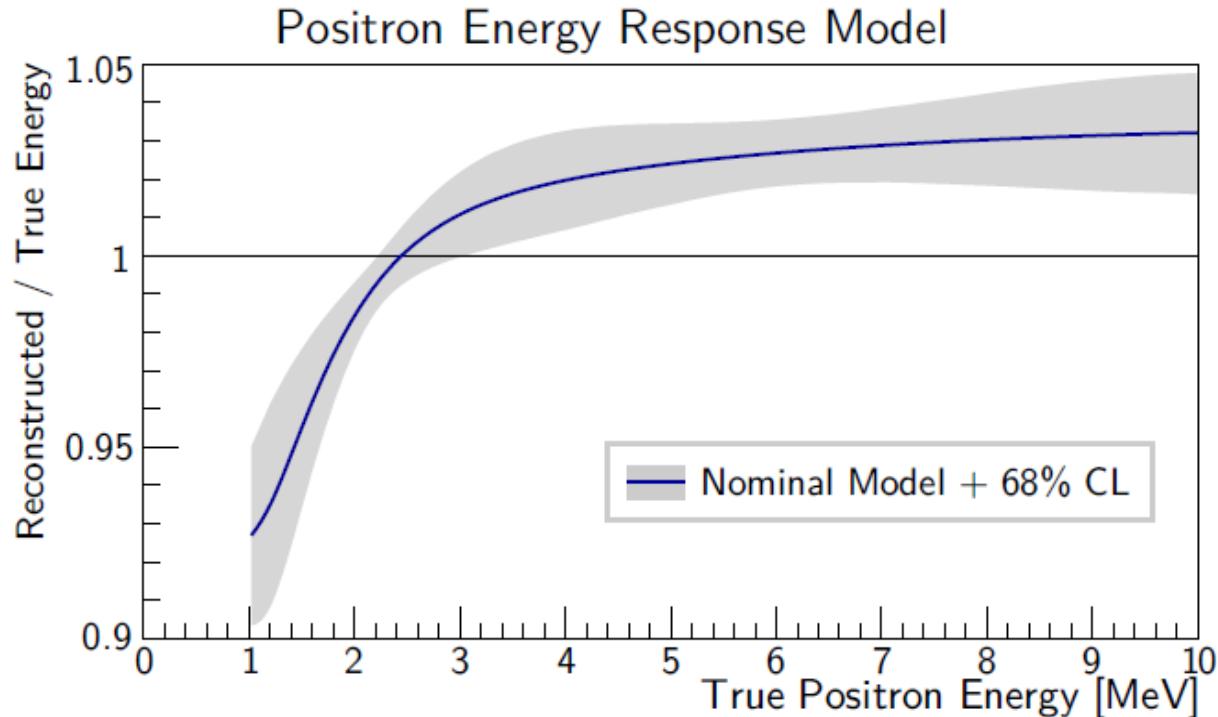
- Same response as electrons

Energy Response Model Constraint



Use calibration gamma sources and continuous ^{12}B spectrum to constrain the energy model parameters

Final Positron Energy Response

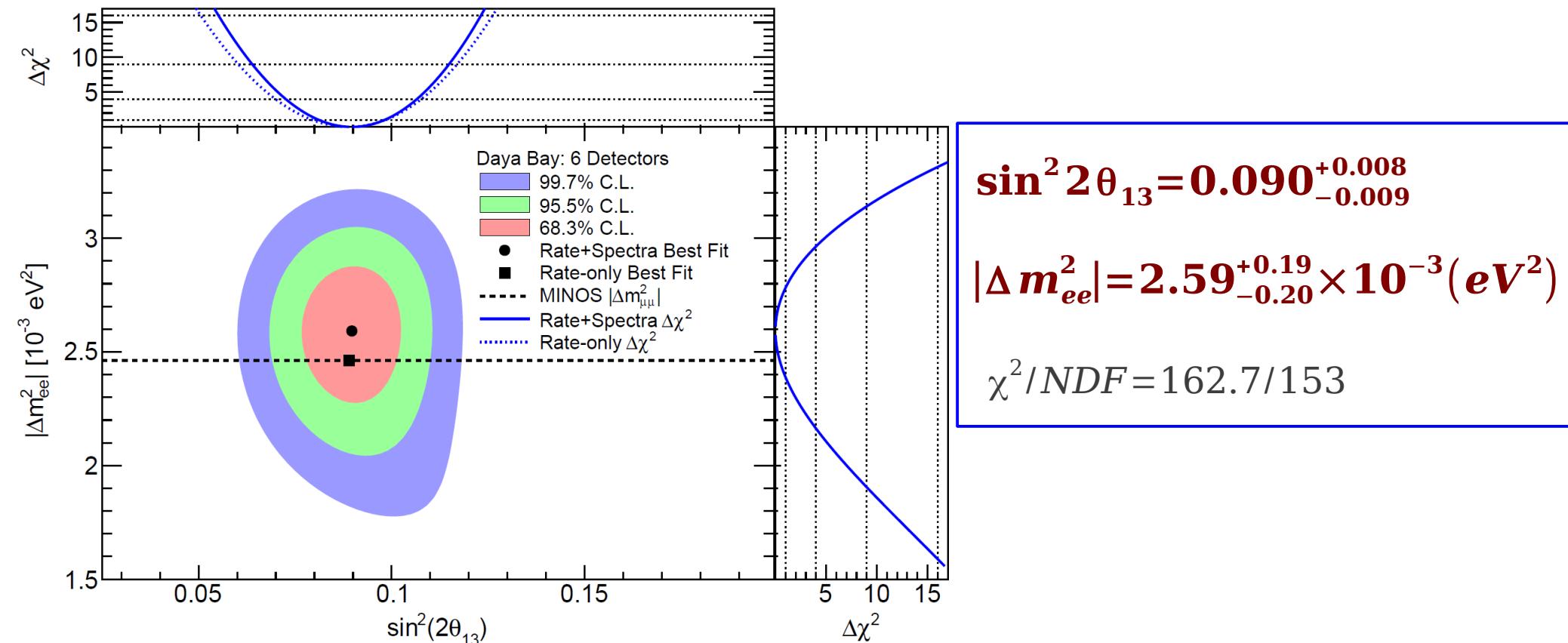


Multiple models are constructed with different parametrization and data constraints

Final Positron Energy Model:

- Conservatively combine 5 minimal correlated energy models
- All remaining models are contained in the 68% confidence interval of the resulting model
- The total positron energy response uncertainty is within 1.5%

Rate and Spectral Analysis



Consistent with the MINOS result

Daya Bay ($\bar{\nu}_e$ disappearance)

Normal $\Delta m_{32}^2 = 2.54^{+0.19}_{-0.20} \times 10^{-3} (\text{eV}^2)$

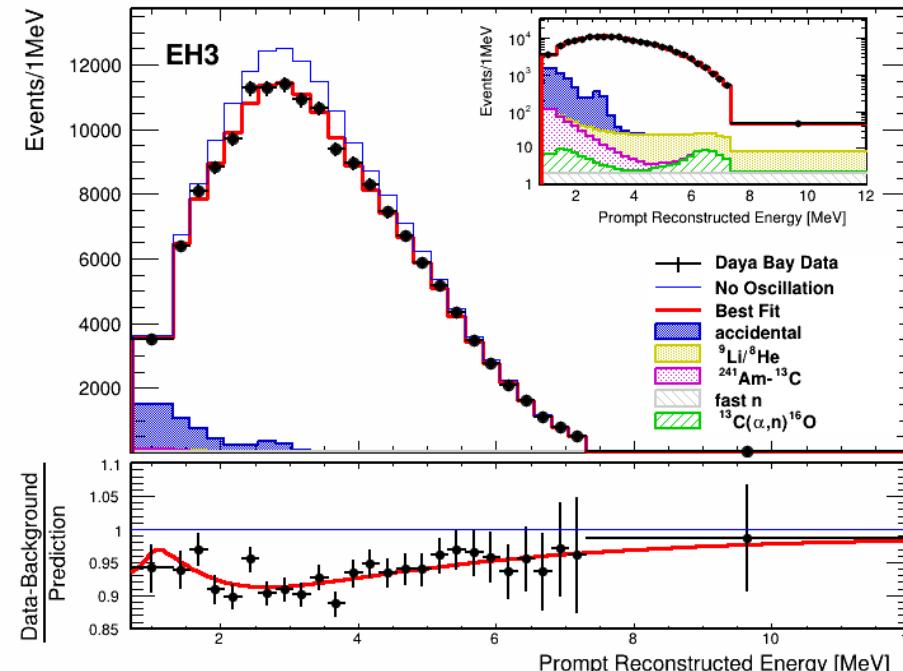
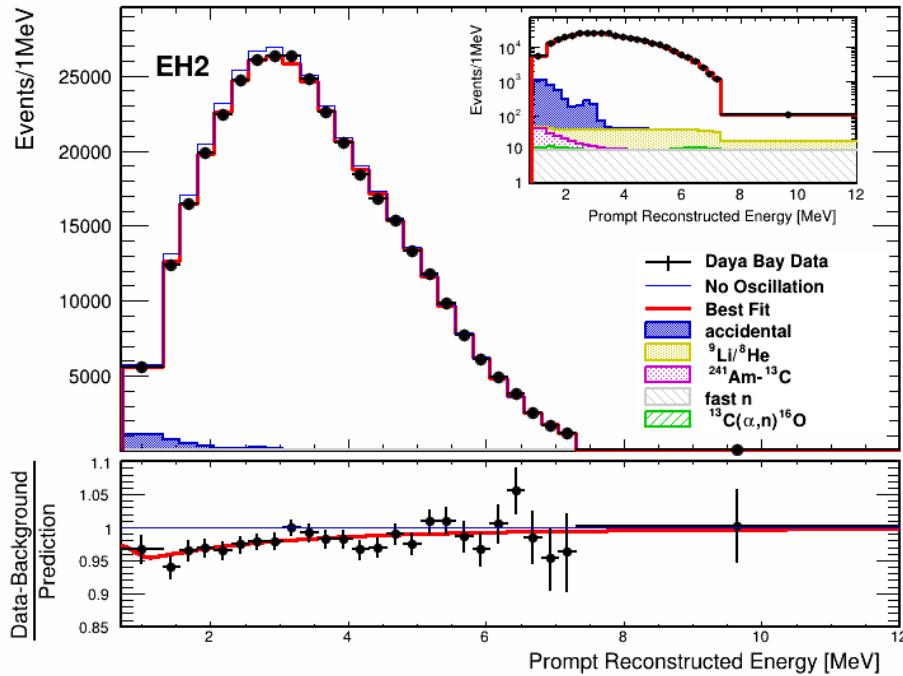
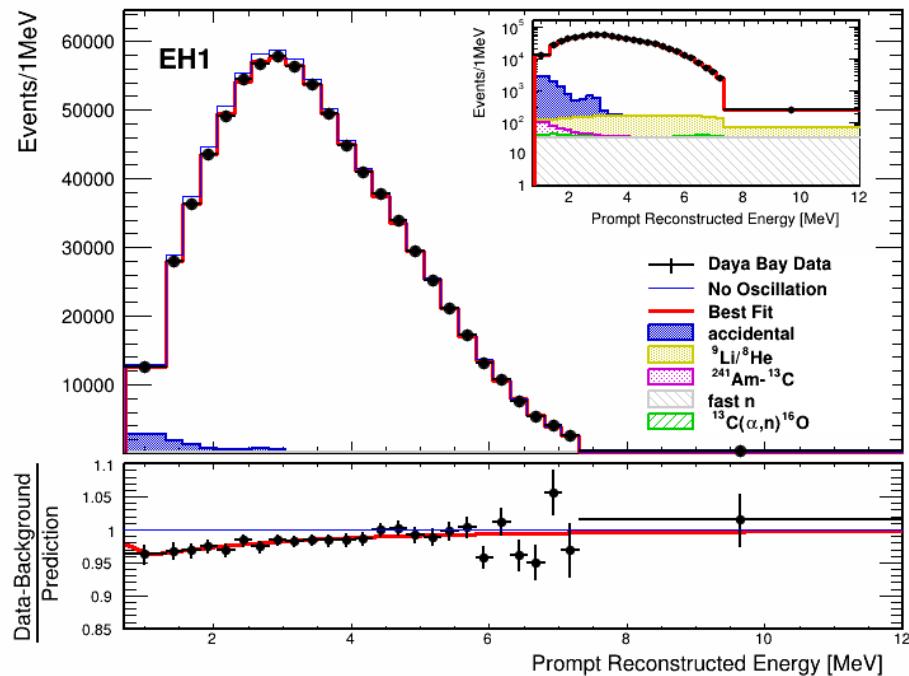
Inverted $\Delta m_{32}^2 = -2.64^{+0.19}_{-0.20} \times 10^{-3} (\text{eV}^2)$

MINOS ($\nu_\mu / \bar{\nu}_\mu$ disappearance)

$\Delta m_{32}^2 = 2.37^{+0.09}_{-0.09} \times 10^{-3} (\text{eV}^2)$

$\Delta m_{32}^2 = -2.41^{+0.11}_{-0.09} \times 10^{-3} (\text{eV}^2)$

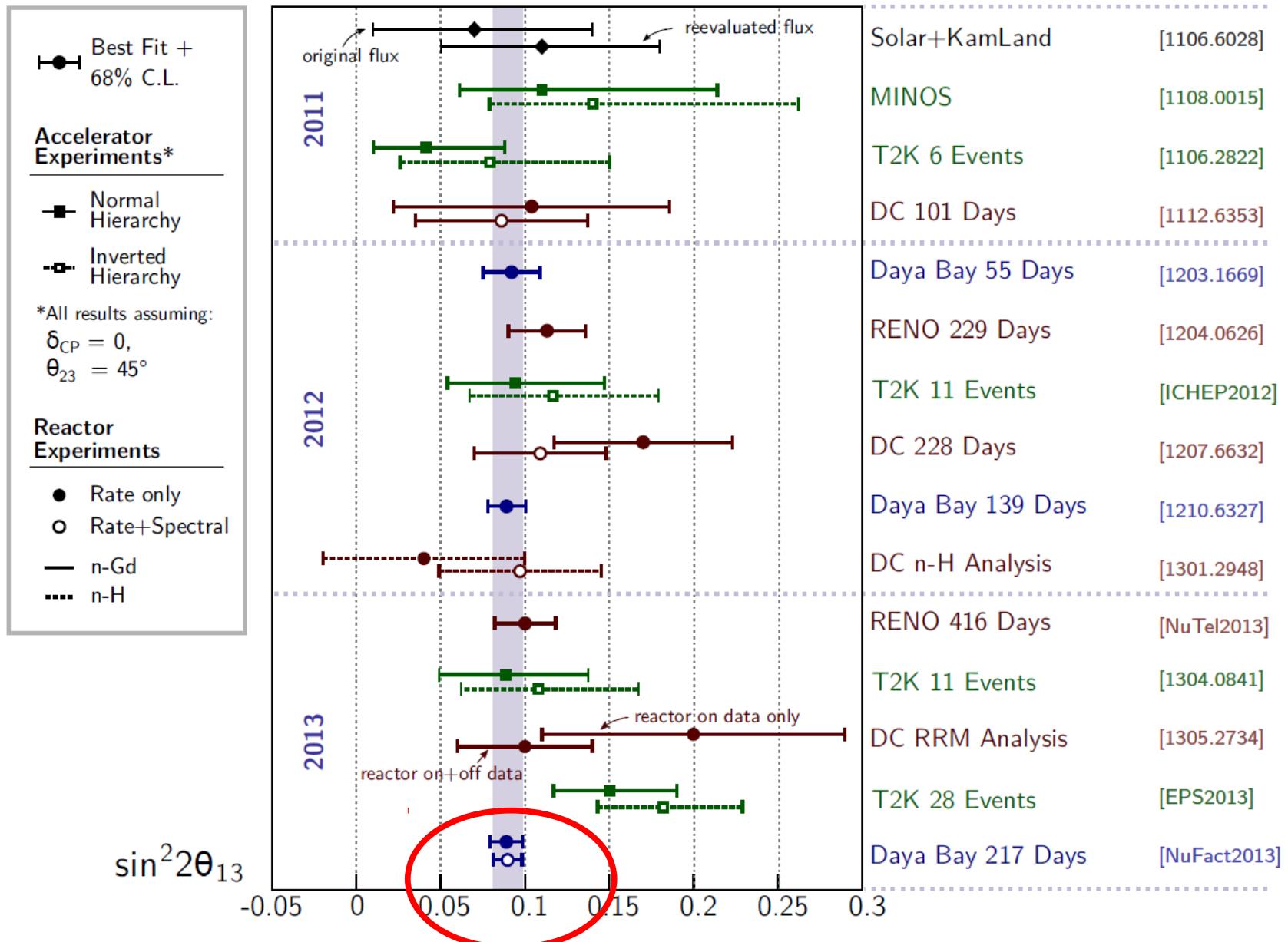
IBD Prompt Spectra



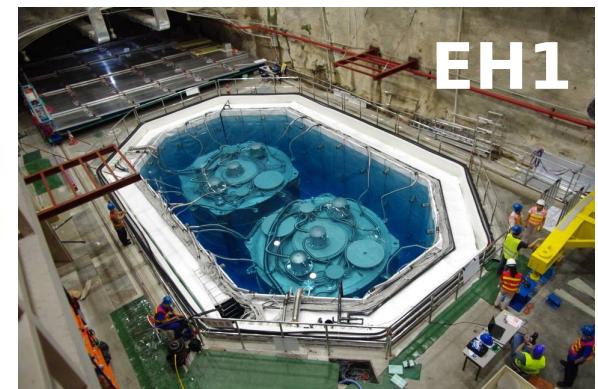
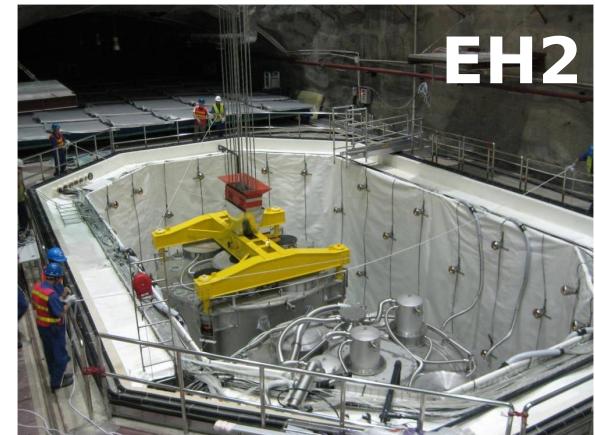
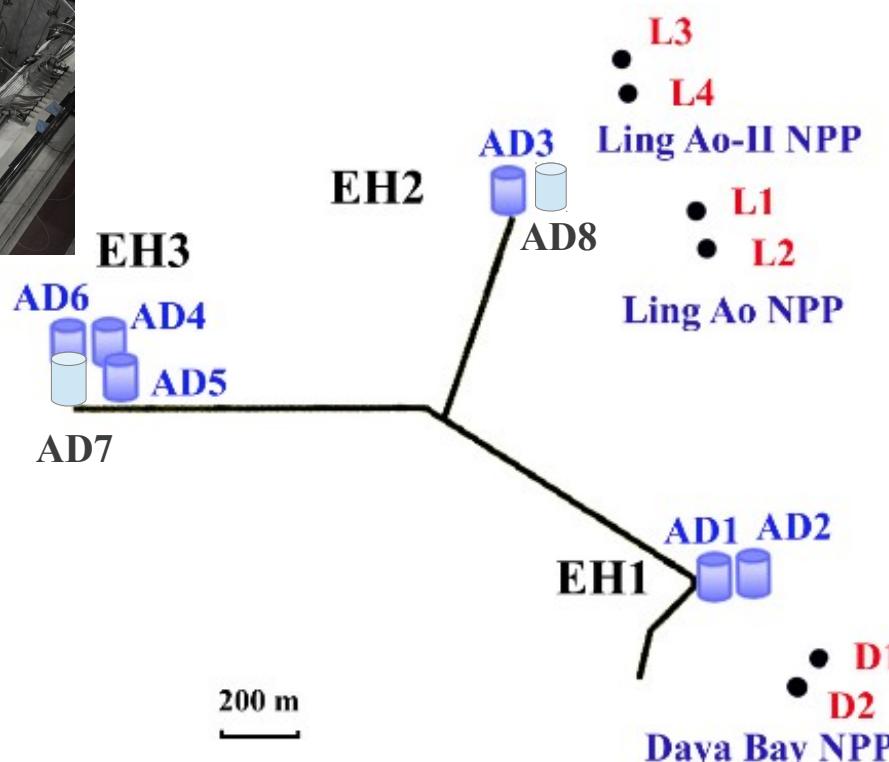
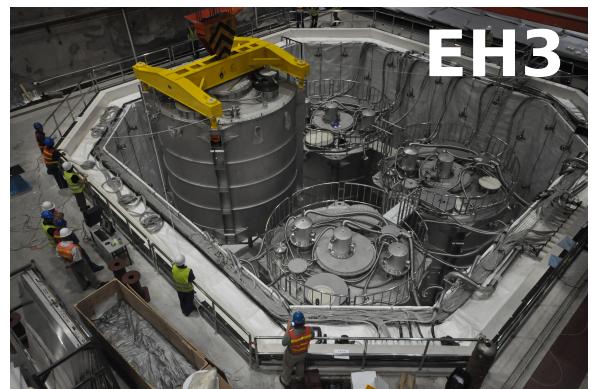
Spectrum distortion consistent with oscillation

- Both background and predicted no oscillation determined by best fit
- Errors are statistical only

Global $\sin^2 2\theta_{13}$ results

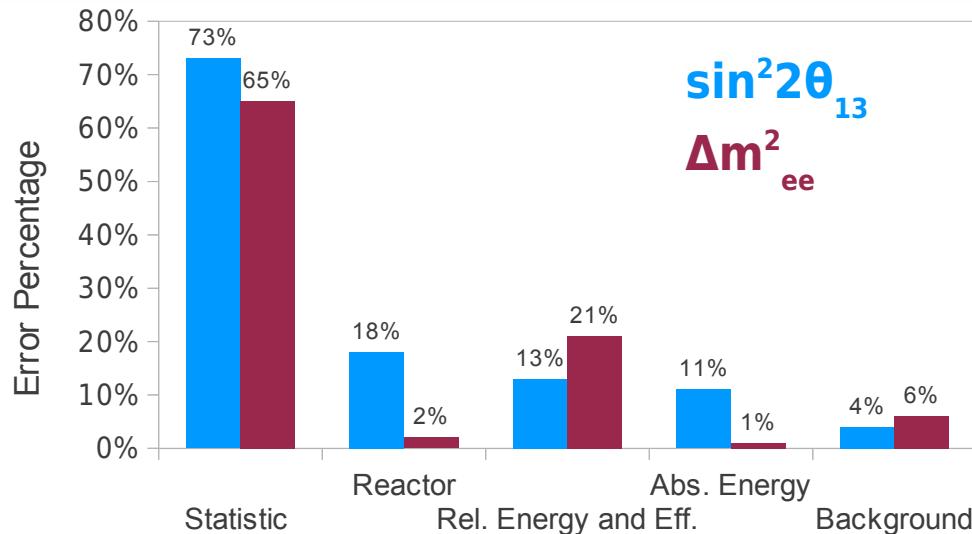
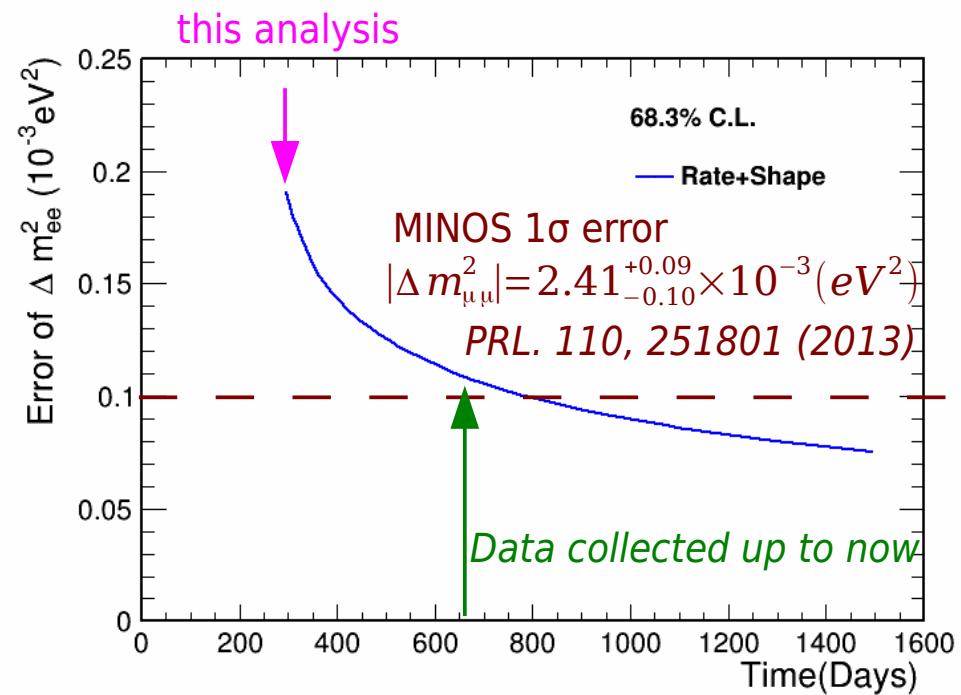
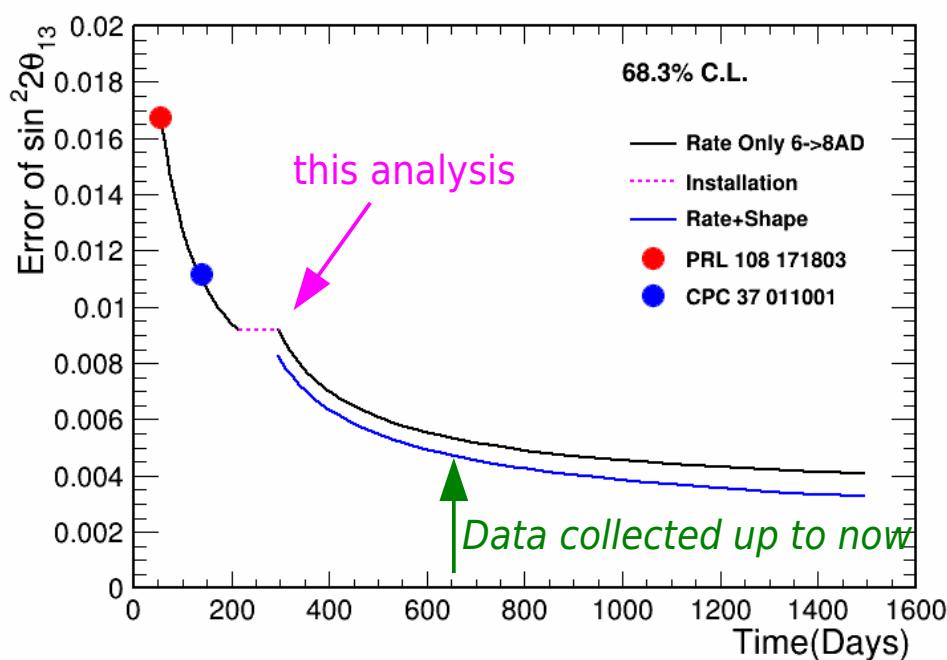


Completion of 8-AD Installation



Two more ADs are installed in EH2 and EH3 in the fall of 2012.

$\sin^2 2\theta_{13}$ and Δm^2_{ee} Sensitivity Projection



- Current error is dominated by the statistical uncertainty
- Daya Bay $\sin^2 2\theta_{13}$ final precision $\sim 4\%$
- Daya Bay $|\Delta m^2_{ee}|$ final precision $< 0.1 \times 10^{-3} \text{ eV}^2$, comparable to the results from ν_μ disappearance channel

Summary

We report currently the most precise measurement of

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

We report the first measurement of

$$|\Delta m_{ee}^2| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

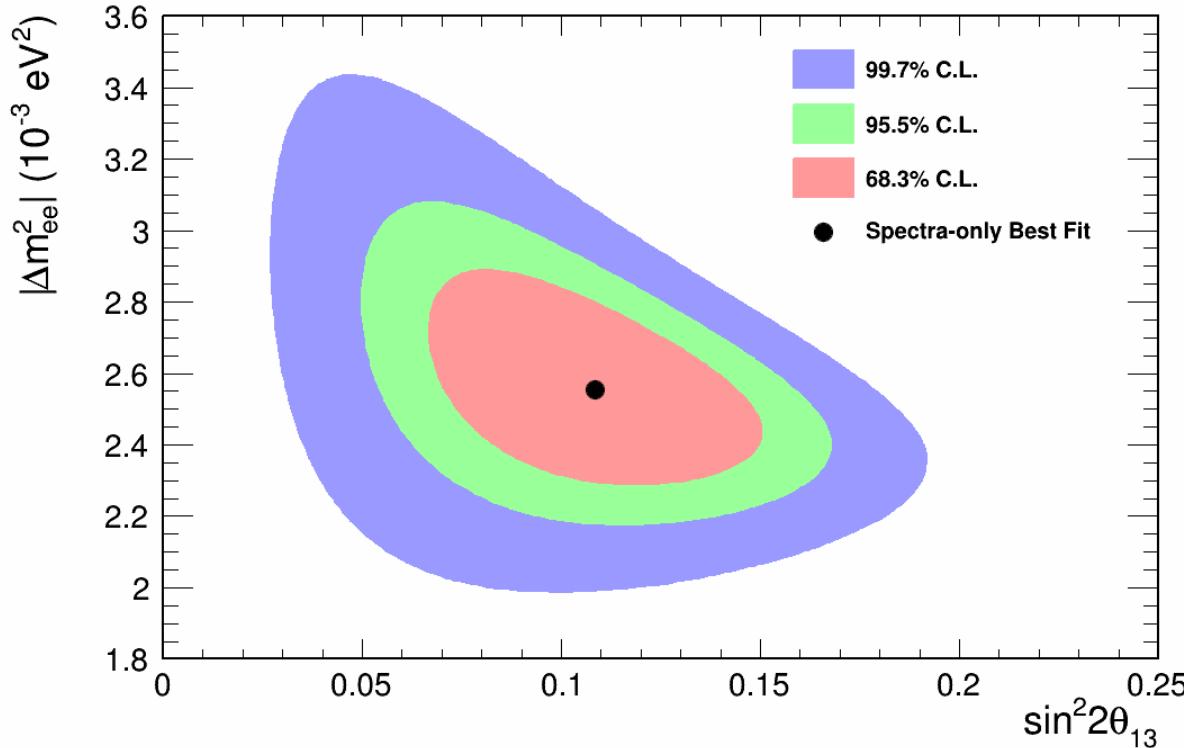
from the electron antineutrino disappearance channel.

Neutrino physics enters the precision era.

Stay tuned for more exciting results from Daya Bay.

backup

Spectra Only Analysis



$$\sin^2 2\theta_{13} = 0.108 \pm 0.028$$

$$|\Delta m_{ee}^2| = 2.55^{+0.21}_{-0.18} \times 10^{-3} (eV^2)$$

$$\chi^2/NDF = 161.2/148$$

- **Spectra only analysis**
 - For each AD, total event prediction fixed to the observed data
 - $\chi^2/\text{NDF} = 161.2/148$ (Float $\sin^2 2\theta_{13}$)
 - $\chi^2/\text{NDF} = 178.5/146$ (Fix $\sin^2 2\theta_{13} = 0$)
 - $\Delta\chi^2/\text{NDF} = 17.3/2$, corresponding to $P=1.75e-4$.
 - Rule out $\sin^2 2\theta_{13} = 0$ at $>3\sigma$ from spectra only information

Strong Confirmation of oscillation hypothesis

Flux Model Comparison

- **ILL + Petr**
 - **Rate Only:**
 - $\chi^2 / \text{ndf} : 0.475584 / 4$
 - $\sin^2 2\theta_{13} : 0.0890$
 - **Rate + Shape:**
 - $\chi^2 / \text{ndf} : 162.131 / 153$
 - $\sin^2 2\theta_{13} : 0.0909$
 - $\Delta m^2_{32} : 2.48 \times 10^{-3} \text{ eV}^2$
- **ILL + Mueller**
 - **Rate Only**
 - $\chi^2 / \text{ndf} : 0.479858 / 4$
 - $\sin^2 2\theta_{13} : 0.0889$
 - **Rate + shape**
 - $\chi^2 / \text{ndf} : 163.444 / 153$
 - $\sin^2 2\theta_{13} : 0.0904$
 - $\Delta m^2_{32} : 2.51 \times 10^{-3} \text{ eV}^2$

Neutrino Flux Prediction

$$S(E_\nu) = \frac{W_{th}}{\sum_i f_i e_i} \sum_i^{istopes} f_i S_i(E_\nu)$$

Reactor operator provide:

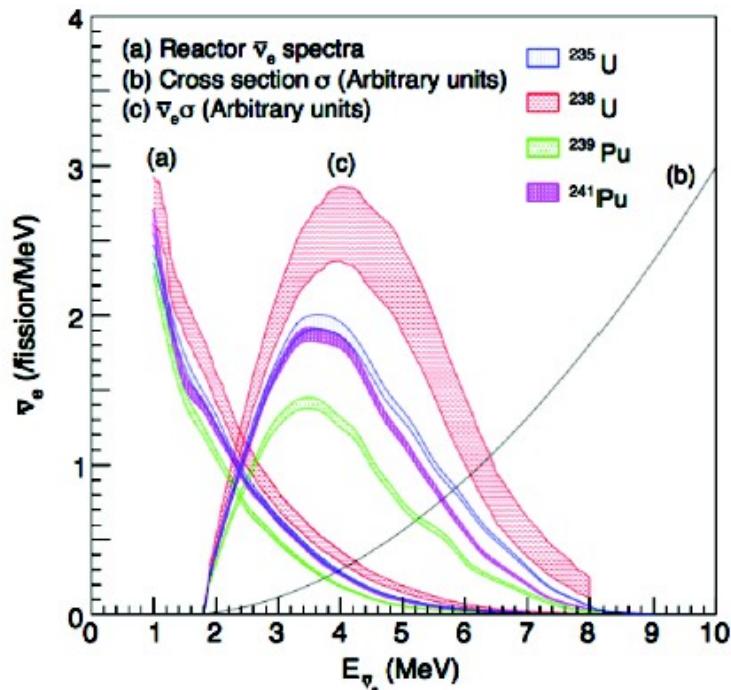
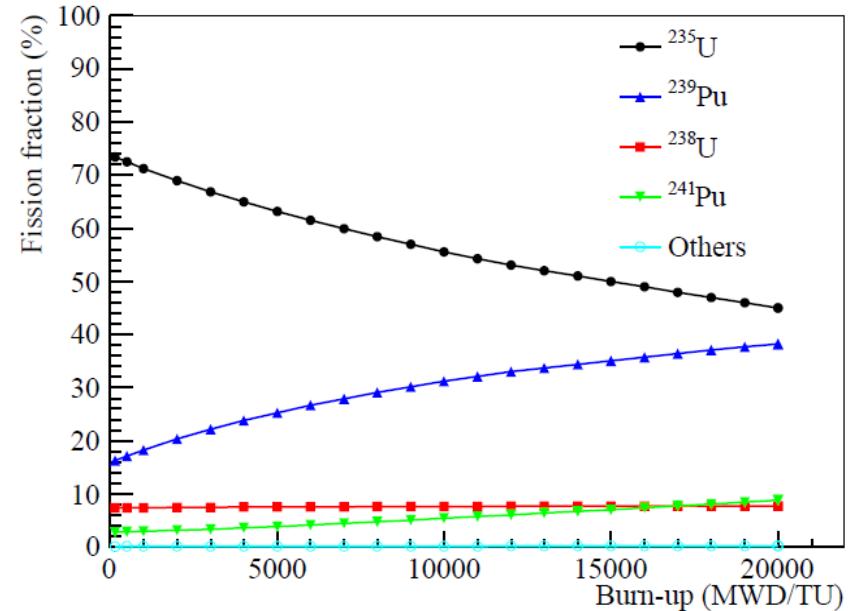
- Daily thermal power W_{th}
- Relative isotope fission fraction: f_i

Energy release per fission: e_i

- V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

- K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
- A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
- P. Vogel et al., Phys. Rev. C24, 1543 (1981)
- T. Mueller et al., Phys. Rev. C83, 054615 (2011)
- P. Huber, Phys. Rev. C84, 024617 (2011)



New reactor neutrino flux model gives 6-8% more neutrinos than the old calculation (Reactor Anomaly)

χ^2 Definition

$$\chi^2 = \sum_i^{det \times E_p} [N_i^{pred}(\theta_{13}, \Delta m_{ee}^2, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b}), -N_i^{data} + N_i^{data} \log \frac{N_i^{data}}{N_i^{pred}(\theta_{13}, \Delta m_{ee}^2, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b})}]$$

$$+ \sum_j^{site \times E_p} \sum_k^{site \times E_p} f_j V_{jk}^{-1} f_k$$

$$+ \sum_l^{abs.E} \frac{\eta_l^2}{\sigma_l^2}$$

$$+ \sum_m^{det \times eff} \frac{\epsilon_m^2}{\sigma_m^2}$$

$$+ \sum_n^{det \times bg} \frac{b_n^2}{\sigma_n^2}$$

Reactor Flux Model Constraint

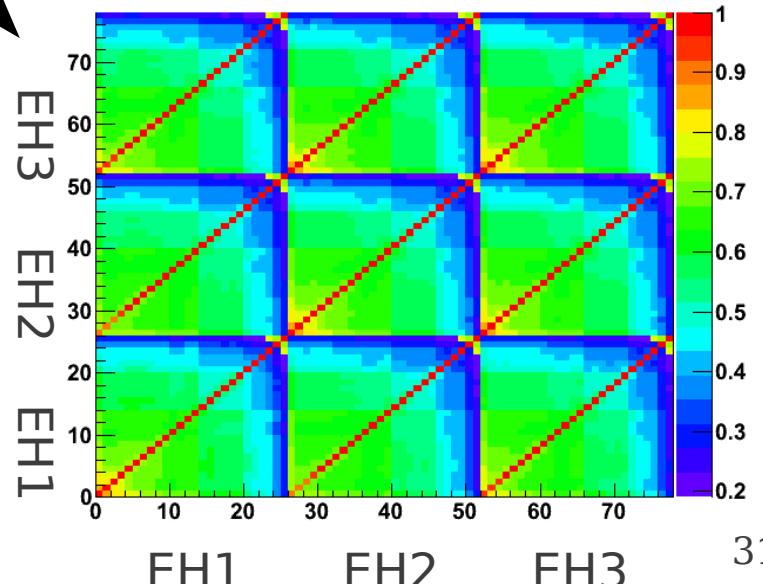
Energy Model Constraint

Detector Efficiency Constraint

Background Constraint

- Binned maximum likelihood method
- Constrain with the uncertainty from reactor flux model, background and relative detection efficiency.
 - Using covariance matrix to reduce number of the nuisance parameters for the reactor flux model.

Far vs. near relative measurement [No constraint on the absolute rate]





Daya Bay Future

Improved precision on oscillation parameters

- Constrains non-standard oscillation models
- Improves reach of future neutrino experiments

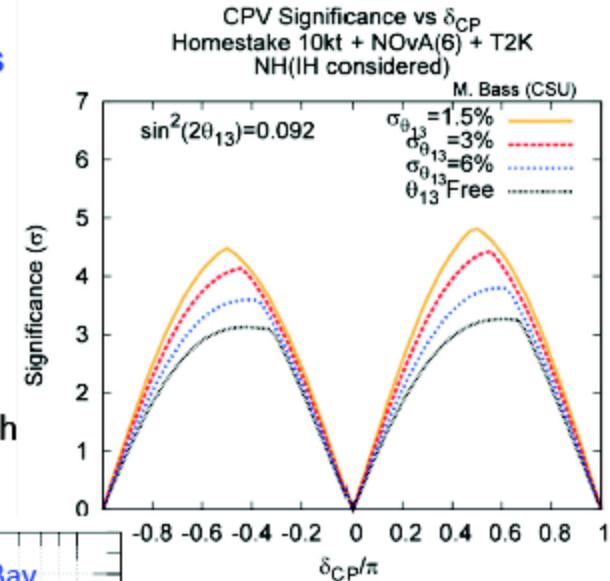
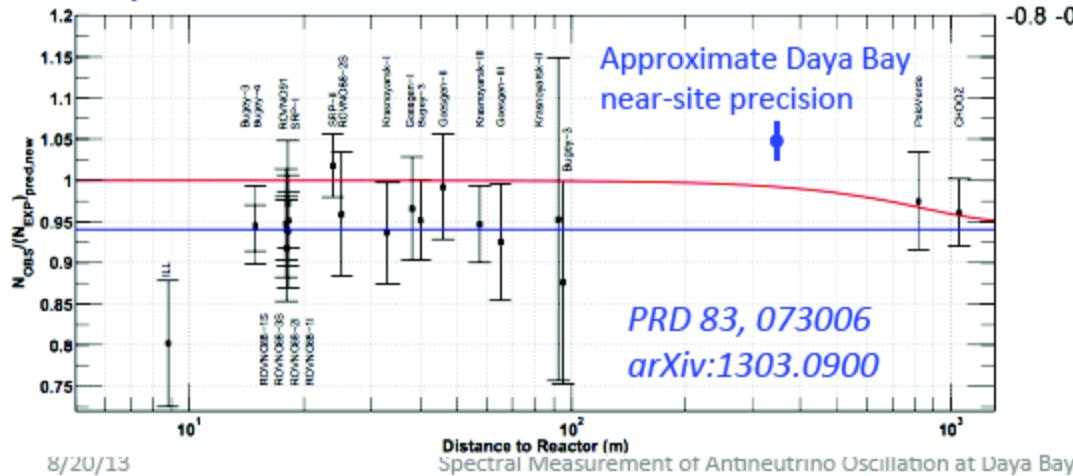
Measure absolute reactor neutrino flux

- Explore the 'reactor antineutrino anomaly'
- Precise spectrum probes reactor models

Cosmogenic Backgrounds

- Measurement of cosmogenic production vs. depth

Supernova Neutrinos



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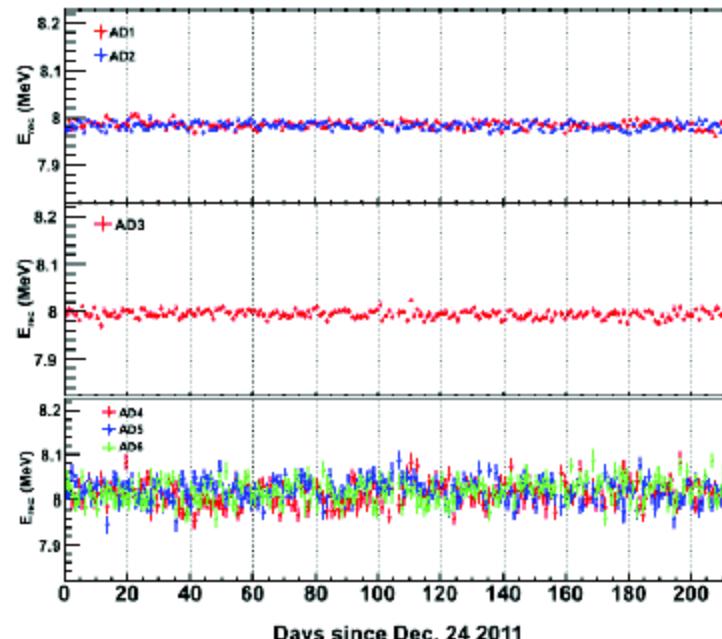


Calibration: Performance

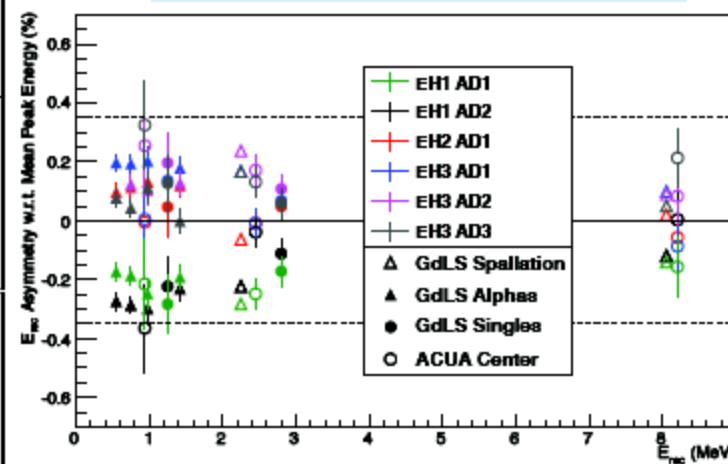
Obtain a stable and consistent Energy Response

After calibration, achieve energy response that is **stable** to ~0.1% in all detectors, with a **total relative uncertainty of 0.35%** between detectors.

Spallation n Gd capture peak vs. time
(after all calibration)



Relative energy peaks in all detectors (after calibration)

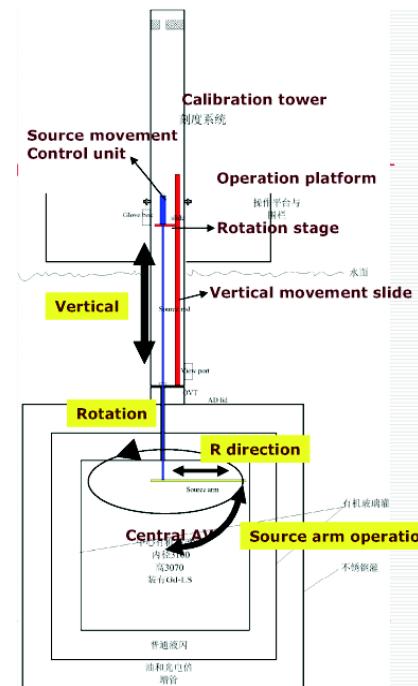


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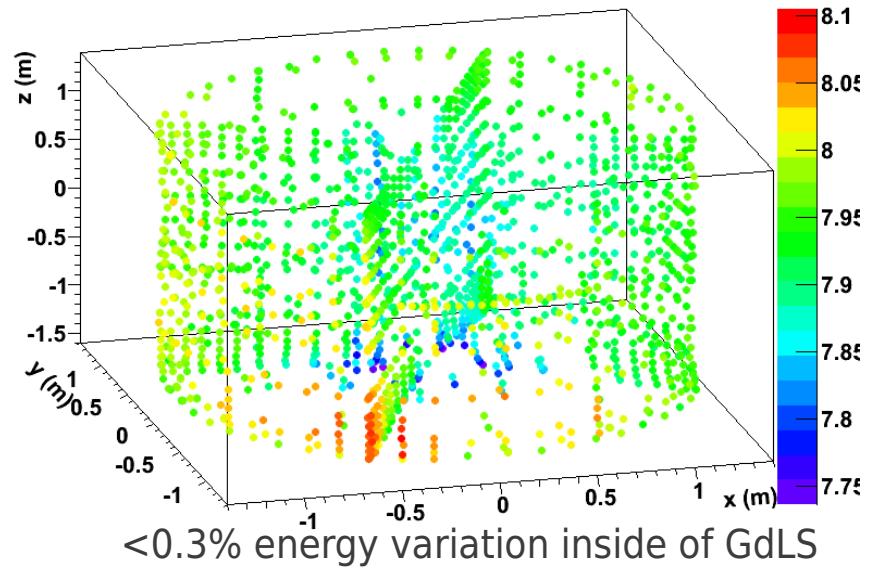
Spectral Measurement of Antineutrino Oscillation at Daya Bay

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Manual Calibration System (MCS)



nGd Energy at Various MCS PuC Source Location

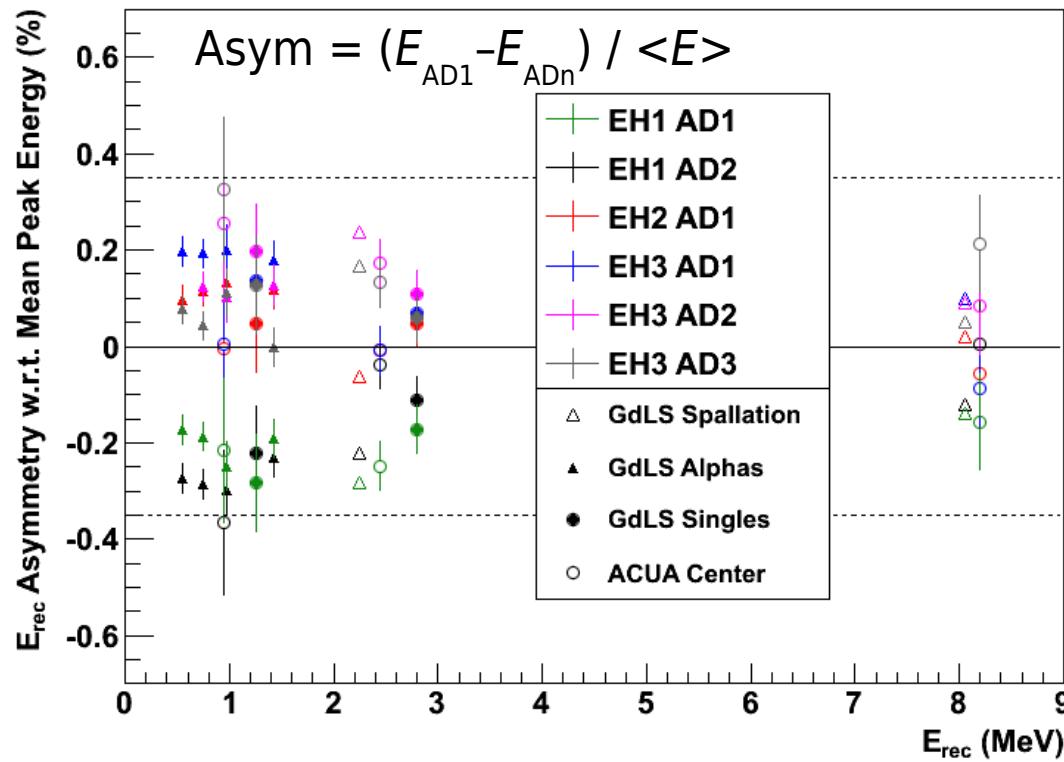


- MCS installed on AD1 during the summer of 2012.
- $^{239}\text{Pu}^{13}\text{C}$ + ^{60}Co composite source 4π source calibration, ~ 1700 locations

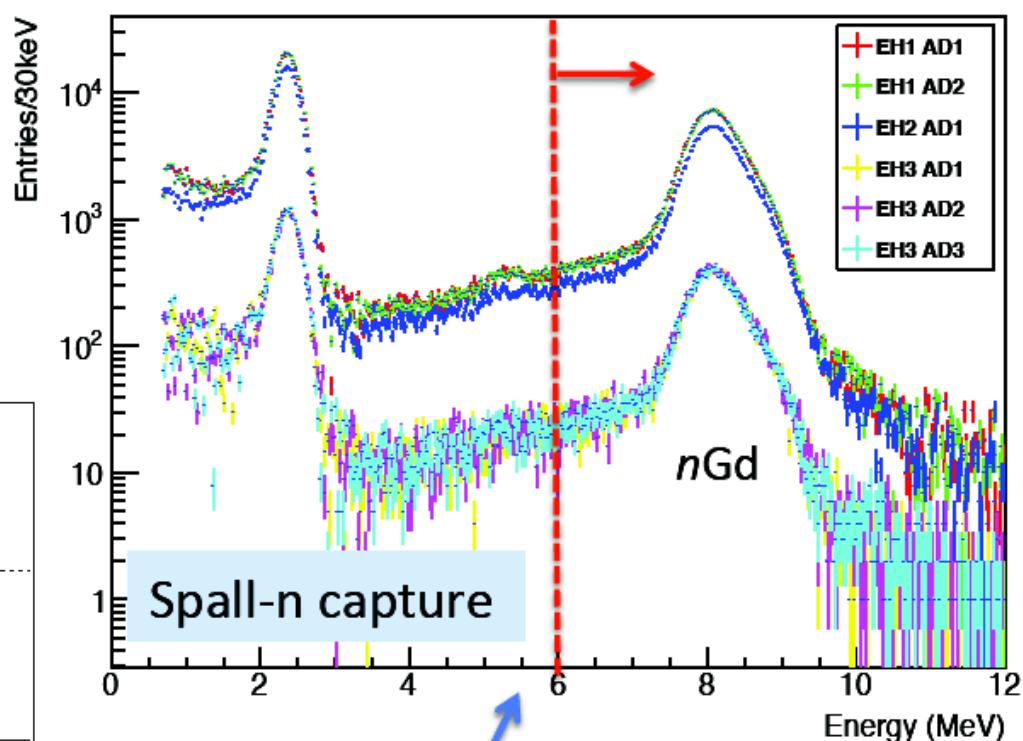
Delayed Energy Cut

Some n Gd gammas escape scintillator region, visible as tail of n Gd energy peak

*Use variations in energy peaks
to constrain relative efficiency*



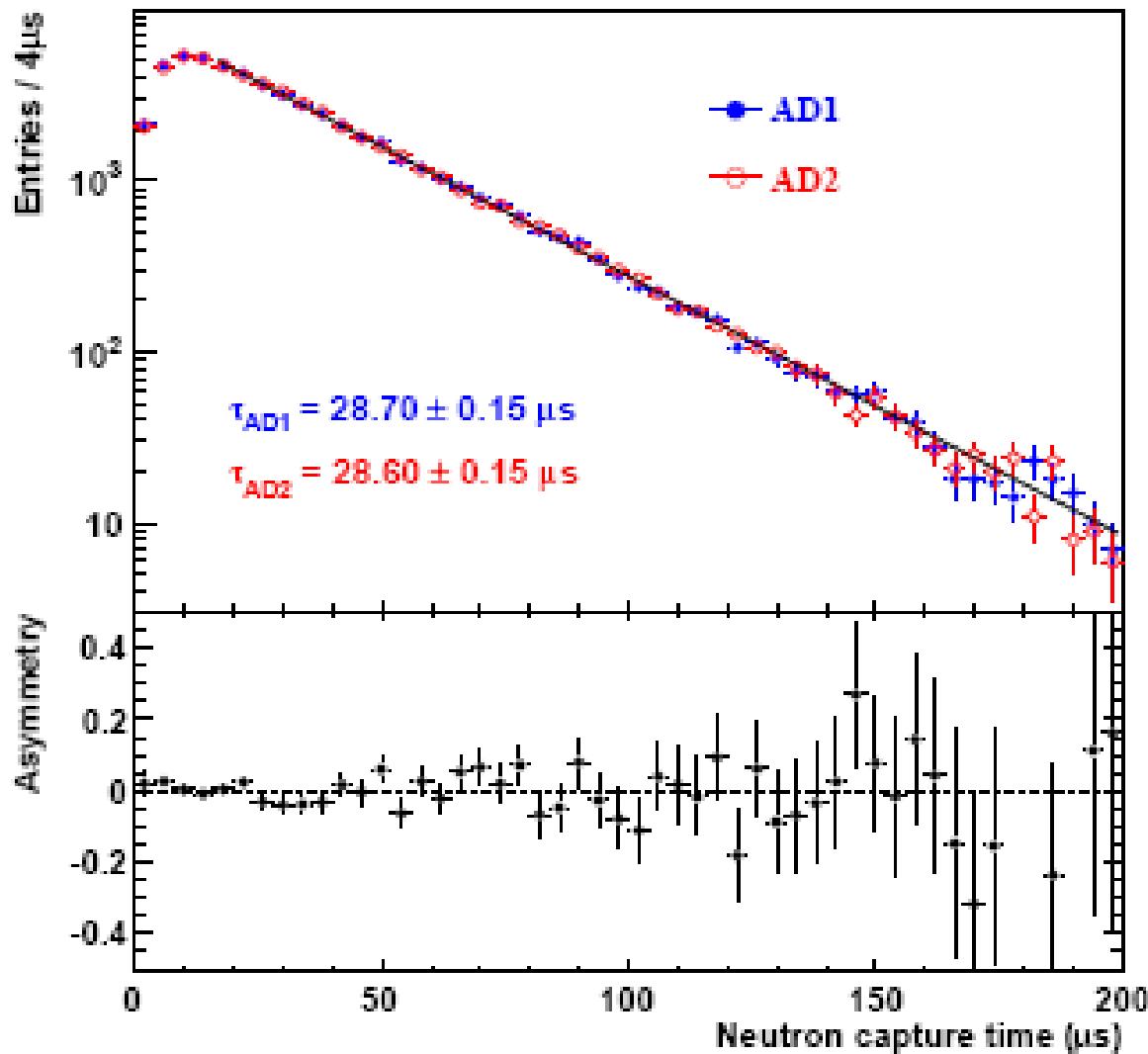
energy peak variation: <0.35%



0.35% relative energy uncertainty
between detectors can cause
 $\sim 0.12\%$ efficiency variation

H/Gd Capture Ratio

Neutron capture time in each detector constrains Gd capture ratio.



Measurement of neutron capture time from Am-C source constrains uncertainty in relative H/Gd capture efficiency to <0.1% among detectors.